Representing Chemistry: How Instructional Use of Symbolic, Microscopic, and Macroscopic Mode Influences Student Conceptual Understanding in Chemistry

by

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ABSTRACT

Chemistry as a subject is difficult to learn and understand, due in part to the specific language used by practitioners in their professional and scientific communications. The language and ways of representing chemical interactions have been grouped into three modes of representation used by chemistry instructors, and ultimately by students in understanding the discipline. The first of these three modes of representation is the symbolic mode, which uses a standard set of rules for chemical nomenclature set out by the IUPAC. The second mode of representation is that of microscopic, which depicts chemical compounds as discrete units made up of atoms and molecules, with a particular ratio of atoms to a molecule or formula unit. The third mode of representation is macroscopic, what can be seen, experienced, or measured directly, like ice melting or a color change during a chemical reaction.

Recent evidence suggests that chemistry instructors can assist their students in making the connections between the modes of representation by incorporating all three modes into their teaching and discussions, and overtly connecting the modes during instruction. In this research, chemistry teachers at the community college level were observed over the course of an entire semester, to evaluate their instructional use of mode of representation. The students of these teachers were tested prior to and after a semester's worth of instruction, and changes in the basic chemistry conceptual knowledge of these students were compared. Additionally, a subset of the overall population that was pre- and post-tested was interviewed at length using demonstrations of chemical phenomenon that students were asked to translate using all three modes of representation.

Analysis of the instruction of three community college teachers shows there were significant differences among these teachers in their instructional use of mode of representation. Additionally, the students of these three teachers had differential and statistically significant achievement over the course of the semester. This research supports results of other similar studies, as well as providing some unexpected results from the students involved.

DEDICATION

First, I would like to thank my mom and dad, Billy and Ellen Wood, who were my first and continue to be my favorite teachers. They instilled in me a respect for education, as well as a love of learning and a desire to know more.

Thanks goes to my sons JJ and Taylor, who have encouraged and supported me after I raised and supported them as a single mom and teacher. Hopefully, you will be proud of your mum, because I am very proud of both of you.

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Introduction

Theoretical Framework for Research

Two broad theories on learning, behaviorist and constructivist, have provided the contextual basis for most research in science education. The behaviorists (Skinner, Pavlov) are deductive in nature, attempting to narrow down and identify the learning variables that might lead to improved performance in student learning. What are the exact experiences students must go through in order to arrive at their own treasure chest of knowledge? The constructivist (Piaget, Vygotski) approach refocuses the attention from the teacher to the learner, and relies on the student to utilize opportunities for learning in order to come up with a framework for understanding, inductively and individually. As Jean Piaget asserted, “knowledge is not passively received, but actively built up by the cognizing [learner]” (Inhelder & Piaget, 1958, p. 328). Constructivists are not as concerned with what goes on in the classroom, but instead focus on what goes on inside the learner. The popular description of this difference is to shift the focus from teaching to learning. (Towns, 2000). Constructivist learning theories emphasize the role of the mind in meaningful learning, and active involvement in the learning process (Bruner, 1966). Internationally, constructivism has become the most important perspective for considering teaching and learning in science, and has been considered as a paradigm or dominant research program in science education research (Taber, 2009).

One of the more important considerations for the constructivist is the prior knowledge of the learner. Much of constructivist theory is grounded in the belief that what a learner already knows is a major factor in determining the outcomes of learning (Ausubel, 1968). Students tend to hold particular idiosyncratic views (often called alternative conceptions) about scientific phenomena and concepts that they bring to science lessons. These unique conceptions about natural phenomena that are held by students are often resistant to instruction because there is a tendency for these conceptions to become firmly entrenched in students' minds as coherent but mistaken conceptual structures (Driver & Easley, 1978). The physical sciences seem especially difficult for students given the influence of their existing knowledge structures, as the explanations that learners create to explain what they see are not always those of the scientific community. Learning is even more difficult when new concepts do not make sense in the context of the existing knowledge structures, and students often revert to their previous alternate conceptions (Treagust, Duit, & Fraser, 1996).

Constructivists are often very concerned with the dynamics of the group; each group/class has its own personality and specific abilities, backgrounds, and perspectives. The learning that goes on within each class is certainly led by the teacher, but the group itself can interact as well, both types of social learning (teacher-led and peer-led) lead to richer knowledge, at least according to Vygotsky (1978). This research employed Vygotskian social constructivism, while also considering Ausubel's ideas regarding prior knowledge. Vygotsky's zone of proximal development (ZPD) has to do with the difference in learning that can be achieved by the student alone, versus the learning that can be achieved with assistance from a capable instructor or within a group. That difference is the ZPD for that particular learner. Vygotsky believed that language was a tool for learning, and that learners must utilize the tools of a culture or specific cultural context to be successful. The smallest unit of study for Vygotsky would be the individual student in a particular cultural/situational context.

Instruction and Environment

The individual classroom teacher has the largest influence on students' learning outcomes (Committee on Science and Mathematics Teacher Preparation, 2001). A good teacher, and more specifically, a good science teacher, is forged through the complex integration of many elements. One such element is an individual teacher's collection of knowledge, which is used to organize the classroom and curriculum. Teacher knowledge has been researched from many perspectives over the past 50 years, reflecting trends in the philosophy of education as well as educational psychology.

In the past, theories on teacher knowledge tended to focus on teacher behavior. This process-product research focus was a search for the effective variables that correspond positively to student achievement (Gage, 1978). The premise of this type of research was to find out what teachers had to know and how they should act in the classroom to positively influence student achievement. Measures tended to be quantitative and objective, with relationships among particular variables (Abell, 2007) of interest to researchers. Teacher knowledge was viewed as a static component that could indeed be measured. In these studies the emphasis was on the "knowledge base" (Reynolds, 1989) that was needed for teaching.

Using only quantitative measures led to a mechanistic view of the teaching profession, which ignored the complexity of individual teachers and their backgrounds

(Doyle, 1990). All teachers have an individual history of experiences in school and life that provide an individual perspective on their own learning and attempts to help others learn, and must certainly be a factor in their teaching. A “cognitive change” (Clark & Peterson, 1986) on the perspective of teaching occurred, and the research focus shifted to teacher cognitions, which are the conceptual framework (Brickhouse, 1990) from which teachers operate in order to construct a learning environment for students. This conceptual framework is built upon the teacher’s practical knowledge (Duffee & Aikenhead, 1992), and practical knowledge is used to guide teacher actions in practice (Brickhouse, 1990; Lantz & Kass, 1987; Verloop, 1992). Practical knowledge is made up of teachers’ knowledge and beliefs about their own teaching practice, and is the core of teacher professionalism. It is action-oriented knowledge (Johnson, 1992), acquired without the help of others, as the teaching experience teaches the teacher. As the teacher learns, the knowledge built is experiential, which is personal and situated knowledge about teaching and learning acquired through experiences and implicit to the individual.

Current theory on teacher knowledge is based largely on the work of Shulman, who tried to understand the essential knowledge necessary for teachers as residing, at least in part, in their specialized content areas. Shulman’s research focused on understanding the specific knowledge necessary for successful student achievement as it pertained to the specific discipline of the teacher – not just subject matter knowledge (SMK), but other types of knowledge more important to the discipline of teaching, especially in the United States.

Subject specific knowledge. SMK is the factual and content knowledge specific to the discipline (Abell, 2007; Gess-Newsome, 1999), and can be either substantive or syntactic (Schwab, 1964). Substantive knowledge has to do with the structure of the discipline in the organization of concepts facts, principles, and theories. Syntactic knowledge is rules of evidence and proof used to generate and justify knowledge, especially important in science. SMK is gained by teachers as they progress in coursework during their own education, and is at first earned by the learner as a student. The content knowledge prerequisite has been evaluated for teachers of both life and physical sciences (Hashweh, 1985; Shulman, 1986, 1987) as it relates to practice. The level of content knowledge has been found to have a significant impact on how subjects are taught (Gess-Newsome & Lederman, 1995).

In comparing a teacher's practice to concept knowledge, teachers weak in SMK have a difficult time choosing appropriate learning experiences for their students. When teaching unfamiliar topics, teachers relate more incorrect information and pose questions at a lower cognitive level (Carlson, 1993) than those with better SMK. For teachers to enhance their students' science knowledge and conceptual understanding, they themselves must have rich and flexible knowledge of the subjects they teach. They must understand the central facts and concepts of the discipline, how these ideas are connected, and the processes used to establish new knowledge and determine the validity of claims (Borko, 2004). In a longitudinal study of science teacher knowledge, the school curriculum was found to be the most influential factor in SMK and organization of that knowledge (Arzi & White, 2004). Thus, teachers continue to develop their SMK as they teach, and that SMK is also constantly evolving as teachers gain experience, learning along with their students.

Clearly, the content knowledge prerequisite is an important factor in teachers' overall knowledge organization, and the depth of SMK has been shown to correlate directly with the number of teaching strategies employed by a teacher (Hashweh, 1986; Ozden, 2008; van Driel, Beijaard, & Verloop, 2001). If mastery of subject matter is the best indicator of teaching success, then the best teachers should be those with PhDs at the college and university level; however, this is not true. In a survey of university science majors who changed degrees, the majority cite poor teaching as one of their top reasons for switching majors (National Science Foundation, 1996). Becoming a good teacher involves more than just a deep conceptual understand of the content of the discipline to be taught, there are many other factors that go into the evolution of teacher knowledge. The study of an academic discipline may not provide prospective teachers with the kind of knowledge necessary to transform their SMK into appropriate instructional activities in the classroom (Sanford, 1988).

Practical knowledge. The study of a particular academic discipline in and of itself is insufficient to provide teachers with the kind of understanding they may need to transform their academic knowledge into instructional activities in their classroom (Sanford, 1988), which is the type of practical knowledge necessary for a teacher's survival. The evolution of practical knowledge in the educator is ongoing and can be immediately applied in the teaching laboratory, so it is also pragmatic. The integration of practical knowledge into teacher practice uses the everyday experiences of the educator and includes norms, values, and beliefs that the teacher develops in the context of the teaching situation (Handal & Lauvas, 1987). This practical knowledge is person and context-bound (Johnson, 1992) and can vary across countries and cultures (Southerland & Gess-Newsome, 1999; Stigler, Gallimore, & Hiebert, 2000). The practical knowledge of a teacher is significantly influenced by peers, and in a study of the role of mentor teachers and their mentee induction teachers, the approach and ideologies of the mentor teachers were found to significantly influence the practical knowledge of their mentees (Zanting, Verloop, & Vermunt, 2002).

Pedagogical content knowledge. Pedagogical content knowledge (PCK) is unlikely to occur unless teachers have developed a deeply principled conceptual knowledge of the content (Smith & Neale, 1989), so there is clearly a content knowledge prerequisite to PCK. The idea of PCK was introduced by Shulman (1987) as pertaining to the knowledge that teachers use to help learners understand specific content. PCK includes knowledge of how particular subject matter topics, problems, and issues can be organized, represented, and adapted to the diverse interests and abilities of learners, and then presented for instruction (Magnusson et al., 1999). PCK is created through reflection, integration, and processing of all these necessary components. Since PCK is developed and shaped via teaching experience (Clermont et al., 1994; van Driel, Verloop, & de Vos, 1998) the best predictor of general PCK is experience, what the teacher learns by doing. Grossman (1990) described contributions that lead to the development of teacher PCK: observation of classes as both a student and a teacher, disciplinary education including specific coursework, and classroom teaching experience.

Magnusson et al. (1999) developed the concept of PCK further, describing PCK as a “mixture” or “synthesis” of five different types of knowledge: orientation toward science teaching, knowledge of science curriculum, knowledge of science assessment, knowledge of students’ understanding, and knowledge of instructional strategies. Other educators have added to and refined the original work of Shulman and the reworking by Magnusson, but the basic premise of the components of PCK remains the same.

Researchers van Driel and de Jong (1999) studied first year chemistry teachers who had at least a master’s degree in chemistry, indicating that they had significant SMK, and found that their development of PCK varied significantly during their first year of teaching. This variance between teacher PCK acquisition was attributed to the variety of events specific to individual teachers, which gave them knowledge of their students’ learning difficulties. Clearly, teachers must take in many different forms and sources of knowledge in their integration to create their own PCK, so it stands to reason that veteran teachers will have the best opportunity for this complex integration to occur. In one study, experienced chemistry teachers possessed a greater repertoire of learning strategies using chemical demonstrations compared to novice teachers, especially as it pertained to addressing particular learning difficulties in students (Clermont, Borko, & Krajcik, 1994). In another study, veteran chemistry teachers were better able to predict and plan around the difficulties experienced by their students due to prior student misconceptions (Geddis, Onslow, Beynon, & Oesch, 1993).

Beliefs. When building practical knowledge, teachers’ beliefs are the filter through which new knowledge is integrated into their practice and conceptual framework

(Pajares, 1992; van Driel et al., 2001). Beliefs play an important role in organizing information and defining behavior (Richardson, 1996) and refer to general pedagogical values as well as to the teaching of a specific subject. Beliefs are guidelines that teachers follow in order to construct a particular educational experience for their students, and can encompass teaching pedagogy as well as content knowledge. Beliefs can be influenced by teachers' biographies (Cole, 1990), their own teachers (Knowles & Holt-Reynolds, 1991), raising children, or the disciplinary backgrounds in which they are teaching (Kobella, Graber, Coleman, & Kemp, 2010). Cronin-Jones (1991) identified four categories of beliefs that most influence curriculum implementation: the teacher's role, the way students learn, the abilities of particular groups of students, and the relative importance of curricular topics. Beliefs are the guiding light of teachers with regard to how they teach and behave in the classroom.

Pedagogical knowledge. Pedagogical knowledge is general, non-subject specific knowledge about the principles of teaching, including different teaching approaches, methods of assessment, classroom management, learners and learning. Once pedagogical knowledge is gained via one discipline, it can aid the acquisition of PCK for those unfamiliar with a particular topic, for example a teacher teaching outside of her or his particular discipline, like a chemistry teacher teaching biology. Both content knowledge and pedagogical knowledge can be the basis to form PCK in any discipline (Sanders, Borko, & Lockard, 1993).

Knowledge of context. An expert teacher has well-formed PCK for all topics taught, and this teaching knowledge is contextually bound. Knowledge of context was defined by Grossman (1990) and requires teachers to understand the specific circumstances in which they teach, including their student population, their colleagues, and the school's political landscape and climate (Little, 2003). This contextual component is personal and situated knowledge about the teaching situation, acquired in the classroom, during informal staff room talks, and even in experiences with parents and administrators. It is highly complex, and not easily assessed or even described (Baxter & Lederman, 1999).

Part of the knowledge of context is an understanding of the specific learner. When using the expert/novice framework for research, teachers' knowledge of their students came mostly from classroom observations and interactions, and this knowledge increases over time (Pinnegar, 1989). New science teachers are less likely to consider the thinking of their students when planning, and more likely to underestimate the potential misconceptions of their students within the context of the subject matter (Frederik, van der Valk, Leite, & Thoren, 1999; Halim & Meerah, 2002; Kokkotas, Vlachos, & Koulaidis, 1998; Nussbaum, 1981; Stocklmayer & Treagust, 1996). Although many new science teachers view the learning of science as transmissional in nature; teachers are constantly assessing and reassessing what and how they teach in their specific context, and in this way, teachers are always learning and eventually take a constructivist view of the learner whether they realize it or not (Osborne, 1998).

Another important part of the knowledge of context is knowledge of the curriculum, which can be either knowledge of mandated goals like state and national standards, or knowledge of specific curriculum programs and materials (Magnusson, Krajcik, & Borko, 1999). Not surprisingly, this knowledge of curriculum is especially helpful to the pedagogical reasoning around lesson planning and instruction (Peterson & Treagust, 1995). Ranking these goals within a particular curriculum or topic is also important, and comes into play for teachers when making the decisions as to the most important things for their students to learn (Geddis et al., 1993).

Teacher knowledge reorganized and integrated into practice. Knowledge organization among teachers is quite complex, and changes as teachers evolve in their profession. What causes knowledge reorganization can originate from many sources, including professional development, in-school or classroom experiences, as well as input from colleagues and even curriculum reform. The effects of all these various influences are certainly cumulative, as the best teachers have been shown to be those with the most experience. To promote the acquisition and reorganization of teacher PCK, varied factors have been shown to be important influences. However, additional disciplinary education (Sanders et al., 1993) and classroom experience (van Driel & Verloop, 2002) seem to be the biggest factors in changing a teacher's practice. The impact of a teacher's classroom experience is enhanced by reflection, (Osborne, 1998) and can improve through careful consideration or action research.

Professional development for teachers is all about teacher activities as they relate to curriculum, instruction and assessment (Hewson, 2007). Types of teacher professional development can include school and district in-service meetings, graduate courses, peer-coaching meetings, sabbaticals, and state/national conferences. Teacher knowledge can be refined by professional development aimed at improving a teacher's knowledge, but there are also additional benefits of professional development for the teacher. Through interacting with other like-minded professionals, teachers can develop professionally and improve their practice within the context of their peers and community (Bell & Gilbert, 1996), with the ultimate goal of any professional development to improve student learning (Hewson, 2007).

There are many factors that go into motivating teachers to seek out and participate in professional development. Catalysts often come in the form of challenges to teachers' beliefs (Veal, 1999) – a realization that what is going on in the classroom is ineffective, or at least problematic (Bell & Gilbert, 2007). Additionally, teachers must feel somewhat isolated and regard the social development and conversations they have with their peers as significantly motivating and helpful professionally. Teachers are more ready to share their experiences with each other and listen openly to their colleagues' critical suggestions and concerns. This social development in essence changes and refines their personal definition of what it means to be a science teacher. Another motivation for teachers to embrace professional growth is often economic in nature, because additional coursework or degrees are usually accompanied by advancements on the salary scale. A study of science teachers by Geelan (1996) showed that those who participated in graduate degree programs in education were motivated to discover new methods and/or pedagogies for their practice as a result of articulating their understanding of teaching and learning. The common language that teachers of a particular discipline develop as a result of scholarly communication is also a source for collaboration amongst them, and can further motivate action research and evolution of practice on the part of the teacher (Baird, 1986).

Common to most successful professional development experiences is a focus on content or practical knowledge (Supovitz & Turner, 2000). Teachers want to know that their time was well spent and that what they learned is going to be immediately applicable in their classroom. Teachers also value the collaboration and feedback they receive from their peers (van Driel, Beijaard, Verloop, 2001), with the most successful professional development programs incorporating an element of time – both for the sustainability of a particular program as well as for individual reflection by the teacher within the context of practice (Davis, 2003). With all the different choices for teacher professional growth, sustained professional development has been proven the most successful. Teachers must develop their own understanding within a culture of learning and improving. Teacher as learner is the most likely professional development to influence student achievement as teachers are engaged in the process of building their practice through learning about content and construction of their PCK.

Orientation of the teacher. The idea of orientation was introduced by Anderson and Smith (1987) as a way to categorize different approaches to teaching science in *The Educator's Handbook: A Research Perspective*. They referred to different teaching orientations as general patterns of thought and behavior related to science teaching and learning, a combination of a teacher's thinking and action. Four teaching orientations were delineated in *The Educator's Handbook*: 1) Activity-driven, 2) Didactic, 3) Discovery, and 4) Conceptual-change. More recently, the description of PCK has been supplemented to include teacher orientation (Magnusson, Krajcik, & Borko, 1999), and much research has been done to define and refine this idea of orientation. Magnusson defined an orientation to teaching science as “a teacher’s knowledge and beliefs about the purposes and goals for teaching science at a particular grade level” (Magnusson et al., p. 97). Magnusson and her colleagues added 5 more orientations to the list in *The Educator’s Handbook*: process, academic rigor, project-based, inquiry, and guided inquiry teaching. Most recently, orientations have been defined as a set of beliefs with the following dimensions: goals and purposes of science teaching, views of science, and beliefs about science teaching and learning (Friedrichsen, van Driel, & Abell, 2011).

Friedrichsen et al. (2011) classified orientations a bit differently, by grouping them into two main categories: teacher-centered instruction vs. reformed teaching. Teacher-centered instruction (didactic and academic rigor) are transmittance models in which the teacher demonstrates the type of knowledge that students must gain through lecture and practicing problems, calculations, and prescribed laboratory activities that are “cookbook” in nature. All lab activities are confirmatory, and practice problems follow a logical progression from simple to more complex. Students are given difficult problems to solve with the goal of training their minds to be efficient and logical thinkers. On the other side of Friedrichsen et al.’s (2011) model are reform-based orientations, which can be divided into two categories: orientations based on reform efforts of the 1960s (process, activity-driven, and discovery orientations), which take place primarily at the elementary school level; and a second category of reform-based teaching that is more reflective of contemporary reform efforts of conceptual-change, project-based, inquiry and guided inquiry orientation(s).

Lantz and Kass (1987) looked at chemistry teachers to determine their orientation, and described three categories: pedagogical efficiency, academic rigor, and motivating students. The teachers themselves used a term, functional paradigm, to describe their complex set of beliefs and resulting orientation as consisting of their views of chemistry (CK and NOS), teaching (PK), students (PCK) and school setting (knowledge of context). Their functional paradigm influenced how they interpreted and implemented curriculum materials (Abell, 2007).

Teacher orientation may be specific to discipline, with physics and chemistry teachers tending to take a more didactic and teacher-centered approach, and biology and life science teachers more likely to see themselves as student-centered in their instruction (Markic & Eilks, 2010). Cheung and Ng (2000) studied 810 science teachers in Hong Kong, and described five different orientations: academic, cognitive processes, society-centered, humanistic, and technological. When comparing the orientation by discipline, they found some interesting differences. Physics teachers were less society-centered than biology teachers. Chemistry teachers were more humanistic than physics teachers. Also significant was that experience did not correlate to orientation; however, beliefs about the cognitive processes of the learner, and the more humanistic orientation(s) increased as teachers gained more teaching experience.

In other research, chemistry and physics teachers at the university level were studied (Trigwell, Prosser, & Taylor, 1994), and the researchers described five different orientations, two of which were teacher-centered, two student-centered, and one in which teacher-student interaction was used. The teacher centered orientations were: transmittance of information and acquiring concepts. The student-centered orientations were: developing conceptions and changing conceptions. The teacher-student interaction orientation also was aimed at development of concepts. These orientations were the compilation of intentions and strategies, and the researchers used a complex analysis and statistical evaluation of the variables in question. An algorithm was created to include the idea that intentions (beliefs) + strategies (PCK) = orientations.

Friedrichsen et al.'s most recent work (2011) questioned the use of categories for orientation and further stated, "we propose that orientations toward science teaching be recognized as consisting of interrelated sets of beliefs that teachers hold in regard to the dimensions listed above" (p. 371). The dimensions mentioned included beliefs about the goals or purposes of science teaching, (the nature of) science, and science teaching and learning. Indeed, orientation is a messy construct (Abell, 2007), but most of the theories regarding this perspective on teacher actions agree that there are those that are teacher-centered in their instruction and those that are student-centered.

Expert chemistry teachers present explanatory artifacts, build on the knowledge and concepts that students already understand, and provide students with all the information that they need to know without being beyond their grasp or over-simplifying the content (Treagust & Harrison, 1999). Chemistry teachers have a big influence on what and how the students learn. They must be experts in their discipline, experienced with pedagogies of different kinds for specific situations, and familiar with the various methods of assessment to determine if, in fact, their students are actually learning chemistry.

Student Learning in Chemistry

College students enrolled in General Chemistry I have had to complete prerequisites for entry into the course, generally a basic algebra class and one year of high school chemistry or one semester of introductory chemistry at the college level. In truth, their mathematics skills are varied from basic algebra to multiple semesters of calculus and beyond. Their previous chemical understanding is based on having had the prerequisites for the course within the last two years and the relative strength of their previous chemistry knowledge depends not only on their previous chemistry coursework, but their everyday experiences and conceptual framework that has been built over years of observation, coursework, personal experience and background. Much of this prior knowledge and may also include many misconceptions that are especially difficult to dispel.

Studies of student learning difficulties in chemistry have been numerous in the last three decades. In a review of this research done by De Jong and Taber (2007), they developed a list of the 12 most common difficulties chemistry students experience. Student difficulties arise in the macroscopic representation in the following ways:

1. Students fail to recognize a process as a chemical change.
2. Students believe that chemical change occurs without any change of properties.
3. Chemical changes are mistaken for physical change.

4. Students view chemical change as transmutation to another substance entirely, or as change of a substance into energy.
5. Students are unaware of the role of gaseous (invisible) particles.
6. Students treat properties of a substance as some kind of extra substance.

Student difficulties arise in the submicroscopic representation in the following ways:

7. Students attribute macroscopic features to molecules or atoms and submicroscopic features to substances.
8. Students fail to invoke atoms and molecules when explaining chemical reactions.
9. An explanation that includes the dynamic nature of chemical reactions is difficult for students, especially as it involves energy changes.

Student difficulties arise in the symbolic meaning in the following ways:

10. Students tend to perceive a formula as representing one unit, and interpret the formulas for compounds in an additive rather than interactive way.
11. Students have difficulty interpreting the subscripts and/or coefficients in a reaction.
12. Balancing chemical reactions is done from an algebraic perspective that does not take into account chemical meaning.

Statement of the Problem

Chemistry is difficult to learn due to communications in multiple modes of representation: symbolic, microscopic, and macroscopic. Past research shows that chemistry teachers tend to rely on the symbolic mode of representation the most. Student conceptual understanding has also been shown to benefit when the microscopic mode is included during instruction. How does instructional use of mode in community college General Chemistry I influence student’s conceptual chemical understanding?

Chapter 2

Literature Review

Learning Chemistry via Lecture

What might individual students experience in the classroom, the laboratory or in life that would lead them to greater understanding of chemical phenomenon? Teachers and chemical educators have struggled with this question for a long time, and in fact chemistry has been taught since the days of the Greeks, who coined the term atomos to describe our current idea of the atom (Liddel & Scott, 2010). Although science education has been researched extensively, the format for delivery of instruction in first year college chemistry has not changed significantly in the last century. The curriculum and required course competencies for first semester chemistry became standardized through organization of major concepts and theoretical principles, which are required because the course is a prerequisite for many other science courses. Articulation of coursework between institutions also creates a need for standardization of the curriculum (Baird, 1992). The topics and associated competencies within each topic are explicit; however, the delivery of instruction and all variables associated with this delivery are left to the individual institution, department, and instructor.

Large lectures are still the most common format for chemistry instruction (ASBMB Report, 2012). The lecture component of most college chemistry courses are set up to mirror the university format so that there is a lecture component with a large enrollment that meets two or three times a week for a total of 2.5 to 3 hours. The lectures are generally held in large lecture halls that are conducive to information delivery.

Traditionally, chemistry is a difficult subject to learn, especially in a passive spectator capacity like the traditional lecture, where the teacher presents what has to be learned, and the student strives to acquire the content presented. Information presented is pre-digested by the professor (Hansen & Stephens, 2000) and students become dependent on the instructor to tell them what they need to know and can avoid taking responsibility for their own learning (Machemer & Crawford, 2007).

In order to benefit from lecture, students must be engaged, have good auditory skills, a high working memory capacity, and have good note-taking skills (Wenzel, 1999). One of the biggest problems with the lecture format is the attention of the learner, which is expected to be continuous during the lecture (Smith, 2001). Learners become absent minded or distracted after a certain amount of time. After only a few minutes of a lecture, 50% of students tune out and never again in the course of the lecture is more than half of the class attentive (Horowitz, 1999). Another of the challenges of traditional lectures in a large chemistry class is that students usually do not have time to process and integrate new information and are forced to passively accept it, hoping to do the integration at home (Milner-Boloton, 2012). They take notes and listen to the best of their ability, and may leave with an incomplete or incorrect idea of the lecture subject. The pace of instruction is set by the instructor, and does not account for the students that need additional time to mull over a topic for understanding to take place (Kulik & Kulik, 1979).

In the lecture, science students are expected to come into the classroom with a set of common prior knowledge. Repeating/reviewing expected information can waste time for the advanced student, learning things they already know, and cause frustration and disinterest for the weaker student (Brown, Collins, & Duguid, 1989). College science lectures are almost always presented verbally, even though today's learners are often strong visual and kinesthetic learners (Johnson, Johnson, & Smith, 1991). The one-way presentation of information that goes on in the majority of lectures makes many college students uncomfortable asking questions, and many will leave with misconceptions and incorrect understandings intact (Bowers, 1986). By not asking questions, the teacher/student interactions are limited, and the teacher may believe that the students understand the information that was transmitted (Chin & Chia, 2004). Interactivity is an essential opportunity for the learner to shape the flow of information by participating in the communication taking place and actively influencing the learning process rather than remaining a passive recipient. A quote by A. B. Arons in *The Art of College Teaching* tells us:

> As we look for improved effectiveness in college science teaching and for the sources of our failures, experience makes it increasingly clear that purely verbal presentations – lecturing at large groups of students who passively expect to absorb ideas that actually demand intense deductive and inductive mental activity coupled with personal observation and experience – leaves virtually nothing permanent or significant in the student's mind. (p. 259)

Many studies have shown that this method of passive learning is not effective (Yager, 1991).

Despite their instructional shortcomings lectures are still an important and common approach to teach science students in higher education (Wessels et al., 2006) all over the world. There are advantages to this method of instruction, including that a large population of students can be educated with coordinated and often limited resources, leading to greater economic feasibility for the institution (Cooney, 2003). In the context of the lecture, traditional instruction is didactic in nature, and teacher-centered.

This method of instruction has been shown to be ineffective – so why does it still predominate? J. N. Spencer, recipient of the 2005 George C. Pimentel Award for Chemistry Education, asserted that chemistry teachers are reluctant to change their method, approach, and philosophy of teaching due to three factors: custom and tradition, cognitive dissonance, and professional definition (Spencer, 1999). First, under custom and tradition, there exists a comfort zone, which is the rationale for teachers to teach as they have been taught: “we can all be expected to teach as we ourselves were taught, which explains why I only lectured at the students as a Princeton professor” (National Research Council, 1997). Second, cognitive dissonance occurs when teachers believe they are doing what is right or necessary, but there is data available to the contrary. In order for change in style or orientation to occur, the teacher must be presented with data that shows their approach to teaching is ineffective. Even then, teachers rationalize away evidence that contradicts their beliefs (Johnstone, 1997). Finally, the professional definition of the teacher includes maintaining standards. Doing anything different from the norm is often viewed as "watering down" the curriculum (Crosby, 1997); maintaining standards and rigor are often part of the culture of science in academia (Anderson, 1994).

Since the majority of instructors teaching first year general chemistry are limited in their delivery and interactions by the lecture format, scheduling, and associated facilities management, the lecture is not going to be soon replaced. However, there are some innovations that have taken place within the context of the lecture to encourage both student-to-teacher interactions as well as student-to-student interactions.

Cooperative learning/peer instruction. Cooperative learning in the college classroom incorporates positive interdependence. Students are given tasks that they perceive the ability to complete more efficiently or more completely if all members of the group contribute. Face-to-face interaction is necessary, and individual accountability should be ensured via the design of assessments (Johnson et al., 1991). A review of research that incorporates cooperative learning in many different science, technology, engineering, and mathematics (STEM) courses, including chemistry, indicating a positive mean effect in support of the assertion that cooperative learning can significantly enhance undergraduate education in SMET courses (Bowen, 2000).

One of the more recent innovations in cooperative learning is the use personal response systems (PRS) or "clicker" quizzes. The typical PRS incorporates a handheld transmission device permitting students to send their responses to a receiver that is connected to some kind of computer software, which then interprets and aggregates the responses in real time. The instructor usually has a choice regarding how publicly or privately the data is displayed, with the most effective strategies using aggregate data from the students to both inform the teacher by uncovering common misconceptions, as well as to allow students to compare their own responses to that of the class as a whole. (Fies & Marshall, 2006). By using the technology to set up cooperative learning networks in the classroom, the students are encouraged to talk to each other during the quiz, so that clarification and peer-to-peer teaching can take place. This sort of interactivity between students and also between students and teacher led to a greater motivation by the students (Moore, 2000) and deeper knowledge structure (Anderson, 2000). The students' attention was kept longer (Fletcher, Hawley, & Piele, 1990) and the students behaved less passively (Simpson, 1994).

Another benefit of the clicker technology is the immediate feedback to the instructor that this technology allows. In some systems, the multiple choice responses sent by the students are tallied and displayed graphically along with the correct response after all responses have been collected. In this way the instructor receives immediate feedback on the knowledge of the students, and the misinformed can remain anonymous if they so desire, protected by the aggregate nature of the response reporting system. The instructor receives immediate feedback on the learning as well as the misconceptions, and can step in with just in time recapitulation of a topic to address a common misconception. Such behavior is especially necessary in the physical sciences in order to prevent later misunderstandings about topics due to missing an earlier topic. One method that has proven especially useful in conceptual change learning in the context of cooperative learning is the clicker problems that lead students into choosing a wrong answer. This method often starts a vivid discussion among the students. The discussion and interaction can be encouraged to further promote student engagement and exploit the benefits of peer instruction (Mazur, 1997).

Clicker systems have already been permanently installed in numerous college and university classrooms, particularly for use in large-enrollment first- and second-year science courses. Instructors are encouraged by their own or their colleagues' evaluation of the technology and are willing to try a new way of interacting with students in the classroom. Numerous research studies have praised the successful contribution of clickers for enhancing students' engagement in large-enrollment chemistry courses (Woelk, 2005) as well as the impact that clickers have on final course grades (Hall, 2005). Clickers in the chemistry classroom show many benefits and few drawbacks, with the use of clickers resulting in measurable increases in student learning when collaboration of some form is used in conjunction (MacArthur & Jones, 2008).

Conceptual change instruction. This type of instruction centers on having students become aware of the conflict between their ideas and the views of scientists. The unique conceptions about natural phenomena that are held by students are often resistant to instruction because these conceptions to become firmly entrenched in students' minds as coherent but mistaken conceptual structures, especially if these conceptions are based in their everyday life experiences (Driver & Easley, 1978). Instead of ignoring or fighting the prior misconceptions of the chemistry learner, this method takes explicit account of these prior misconceptions and incorporates cooperative learning into encouraging students to modify, replace or refine their misconceptions via opportunities to verbalize these misconceptions and discuss with their peers and the instructor (Bergquist &

Heikkinen, 1990). According to Herron (1996), teachers must understand the sources of students' misconceptions and learn how to overcome them to improve learning in chemistry. In addition, students must be dissatisfied with their existing ideas and beliefs before they are interested in changing them. There are four conditions necessary in order for conceptual change in the learner to occur. The first condition states that disequilibrium or cognitive conflict with the prior misconception must take place through making students aware of their own ideas, asking for explanations of familiar and discrepant events, and debating alternative conceptions. The second condition states that a new conception has to be intelligible (the learner must be able to understand the new conception). The third condition states that a new conception must appear initially plausible, i.e., can this really be a better explanation? The last condition is that the new concept must be fruitful, which means that the learner must be able to use the new concept to resolve problems and open new areas of inquiry (Posner, Strike, Hewson, & Gertzag, 1982). Orchestrating all these conditions in the context of the lecture format is at best difficult, and cooperative learning and the social interaction that it encourages are certainly beneficial.

Demonstrations. Student thinking is heavily influenced by sensory information that students are able to experience directly (Novak & Gowin, 1984). Demonstrations can be used to break up the class period or start the class with an opportunity for a moment of perplexity and a question (Meyer et al., 2003), or used as the theme for instruction. Demonstrations provide the teacher an opportunity to address the more visual and kinesthetic learner (Gardner, 1993). Students who typically struggle in more formal classrooms are the first to be drawn into and benefit from a demonstration activity (Sousa, 2001). Demonstrations can even be used to measure student learning (Bowen & Phelps, 1997). Demonstrations assist in creating a positive classroom feeling and a sense of community. Shared experiences of interest energize a classroom, breathing life into class work, tapping student emotions and creativity, and evoking a sense of shared mystery (Moore, 2000). Teachers and students draw closer together and discussion based upon personal interpretation and shared experiences results.

Demonstrations take a lot of time to set up and coordinate with the curriculum, and many facilities do not have the necessary safety considerations to be able to perform large-scale demonstrations. When time and place permit, demonstrations have been shown to be productive at assisting in student understandings (Meyer, Schmidt, Nozawa, & Panee, 2003).

Learning Chemistry in the Laboratory

The laboratory portion of most college chemistry courses utilizes smaller break-out sections of the lecture. The lecture may or may not be coordinated with the laboratory material, and the same instructor may or may not be the same for corresponding lecture/laboratory sections. This model creates lecturers that are often disconnected in topic and sequence from the laboratory instruction. The content and relationships presented in lecture may be disjointed and/or asynchronous with those from experiments in the laboratory.

The chemistry laboratory is an expensive way to teach students, with necessary reagents, materials, equipment and instrumentation necessary to deliver the quality of instruction expected making chemistry one of the more expensive sciences course for any college to offer. Many are now beginning to question whether the inherent value of the laboratory experience is worth the expense at the undergraduate level (Hilosky, Sutman, & Schmuckler, 1998). There are those (Hawkes, 2004) who believe that the usefulness of the laboratory experience does not outweigh the expense enough to make it a necessary component of instruction for non-chemistry majors. Several studies have shown that laboratory work made no significant difference in tests of information, practical application, scientific attitude, or laboratory performance (McKeachie, 2007). Although laboratory courses are effective in improving skills in handling apparatus or in visual-motor skills, laboratories are not effective in teaching the scientific method.

Most college chemistry laboratories utilize verification labs that teach technique, protocol, and how to handle reagents necessary in the discipline. It is rare that inquiry is used, since the volume of students and standardized curriculum make it difficult to individualize the curriculum (Domin, 1999). The verification format has evolved specifically to fill a need to minimize demands on time, space, equipment, and personnel in the college laboratory setting (Montes & Rockley, 2002). The laboratory experiences of first year chemistry students are largely conformational in nature, due to many factors. First, the experiment needs to be run in the allotted time frame, usually 2.5 to 3 hours. Second, these verification experiments lend confidence to the instructors because they are well tested, simple to prepare, and easy to grade. Finally, the instructors value the adaptability of the experiments, in that they can be scaled up or down, depending on class size (Montes & Rockley, 2002).

In 1989, the National Science Foundation put together a task force to evaluate the general chemistry curriculum at the college and university level. Their recommendation was to restructure the curriculum of both the lecture and the laboratory around the laboratory experience, so that the lab played a more central role in the organization of curriculum (Lloyd & Spencer, 1994). Focusing on the laboratory experience entailed a closer examination of how well lecture topics and laboratory experiences relate – not only did the lecture not connect or relate to lab, but students were not learning anything new in the context of the lab. A comprehensive review article on laboratory instruction also shows that labs have little measurable effect on the educational achievement of students (Lloyd & Spencer, 1994). Additionally, Lloyd compared the way different laboratory activities resulted in very different learning outcomes. He concluded that these differences demand rigorous studies of the effects of laboratory teaching and learning.

Typical laboratory instruction for first year general chemistry has been categorized into “styles” (Domin, 1999), including: expository, inquiry, and problem-based. The expository laboratory lesson is “cookbook” in nature, and emphasizes following specific procedures to collect data. Students do not have a hand in designing the experimental protocol, or even the question to be investigated. These expository experiences are usually verification in nature, with the data collected by students used to verify some scientific theory or fact already known (Tobin, 1994). This type of lab asks students to operate at a much lower cognitive level than is necessary in a complex topic like chemistry. Expository experiences are deductive in nature, where students apply a general principle to explain a specific phenomenon (Spencer, 1999) rather than using observations to develop a general principle (as in inquiry or problem-based). Since the time/space/personnel factors are so significant in organizing and delivering the chemistry laboratory to the undergraduate, it is going to be difficult to move entirely away from the traditional expository style of laboratory instruction (Herrington & Nakhleh, 2003).

In contrast to the traditional behaviorist-based expository laboratory experience, inquiry based laboratory experiences are constructivist and inductive in nature, have an undetermined outcome, and require the students to generate their own procedure (DeBoer, 1991). These experiences involve the student more, contain less direction, and give the student more responsibility for determining procedural options. In the process, the student gains ownership over the laboratory activity. Inquiry is the gold standard in today's science classroom, but there are many problems with initiating its delivery. Teaching science as inquiry requires that teachers have a highly structured and deep conceptual knowledge base (Gess-Newsome, 1999).

Within the scope and sequence of instruction, a major difference between traditional and inquiry instructional strategies is the placement of the laboratory in the sequence of instruction. In the case of the traditional laboratory, it comes second after the presentation of the concept, whereas in inquiry it begins the instruction (Abraham, 2011). Coordinating the lecture and the laboratory experience to ensure this curricular placement is an additional challenge that causes difficulty using inquiry labs in first year chemistry. Add to this the uncertain nature of the needs of students during their inquiry as the sheer volume of students that may go through an undergraduate laboratory and the problems in offering inquiry level activities become overwhelming to many institutions.

Some colleges and universities are moving to adopt inquiry experiences gradually, in order to transition more smoothly considering all the extraneous variables that influence the delivery of inquiry. In one study, a single laboratory experience that was expository in nature was changed to an inquiry experience (Cacciatore & Sevian, 2009) and compared to control groups that used only the expository lab experiences, and the change caused the treatment group to perform significantly better than the control group on complex experimental design and data analysis for open-response problems that were directly related to the content – stoichiometry – presented in the lab. There was also a positive treatment effect on student learning of chemical content; however, this effect did not extend beyond the chemistry content addressed the inquiry experiment.

Project/problem-based learning (PBL) is student-centered and focuses on helping the student to acquire skills necessary for lifelong learning, including: self-direction, application of knowledge, problem solving, reflection, and self-evaluation (Schmidt & Moust, 2000; Slavin, 1997). PBL was originally developed for medical school programs (Barrows & Tamblyn, 1980) and was later embraced for use in the science classroom. During a PBL laboratory experience, students work in collaborative groups under the guidance of the teacher in order to solve "real world" problems, and in the process build knowledge socially, where the knowledge is distributed and shared as in social constructivism (Ram, 1997). The problems presented to the students are nested with the course competencies, and the students are led to understand course curricula via the necessary application of skills when solving the problems as a group.

In chemistry, there are many references to successful adaptation of the PBL strategy (Chin, 2004; Dods, 1996; Groh, 2001; Hughes, 1993; Ronis, 2001; Senocak et al., 2007). PBL has taken analytical and instrumental chemistry by storm and proven especially useful as a contextual paradigm that utilizes the popular interest in forensics. (Belt, Evans, Mcreddy, Overton, & Sumerfield, 2002; Cancilla, 2001; Hudle & White, 2000; Wenzel, 1995; White, 2001; Yuzhi, 2003).

Although many proponents of the PBL methodology report on “how to” alter curriculum to the PBL mindset (Delisle, 1997; Gallagher et al., 1995; Ronis, 2001), there are not many that report on comparisons of student achievement or attitudes when using PBL. Of the few to perform a controlled experiment or intervention strategy using PBL, Diggs (1997) reported that PBL curricula had positive effects on student attitudes towards science and achievement in science, and promoted deeper understanding. Tarhan and Acar (2007) used a PBL unit to teach cell potential, and found it effective in increasing student achievement, remedying formation of alternate conceptions, and improving the development of social skills. This method of learning is most often seen in the laboratory, since the smaller populations can lend to more individualized instruction.

The modern college chemistry lecture classroom and chemistry laboratory instruction have not changed significantly, although learning theories have morphed to include many different variables regarding the best possible learning experience for the chemistry student. A disconnect exists between changes in learning theories in comparison to instruction that has remained static, more so at the college level in comparison to the secondary school.

Trigonal Planar Nature of Science and Chemistry

Most recently, communicating chemistry has been organized into a model originally proposed by Johnstone (1991), and uses a molecular geometry metaphor which seems to resonate with many chemistry instructors. This metaphor of trigonal planar categorizes the different ways of representing chemical phenomenon into three categories: macroscopic, microscopic, and symbolic modes of representation. Johnstone (1991) asserted that conceptual understanding in chemistry is difficult because the representation of particle interaction involves all three different modes of representation.

The first mode of representation, that of macroscopic observation, refers to the tangible, visible, and experiential that can be viewed with the naked eye. Many everyday experiences of the learner are incorporated into this mode of representation. A beaker is emitting gaseous vapors, a precipitate is formed, an ice cube melts or a solution changes color. In addition student misconceptions often come into play due to the learner's mental explanations for observed phenomenon.

The second mode of representation is that of microscopic or molecular, which refers to the basic components of substances, how atoms and ions form molecules; and how that arrangement changes during a chemical reaction. This mode of representation also includes the motion and distribution of these particles in different states of matter, and the changes in motion and distribution due to temperature, pressure, concentration or chemical reaction.

The third level of representation is that of the symbolic: the symbols, equations, graphical representations, and calculations associated with the quantitative nature of chemistry (Harrison & Treagust, 2000; Kruse & Roehrig, 2005). Johnstone (2010) held that a student must be experiencing, thinking, and communicating at all three levels in order to have a deep conceptual understanding of chemistry, so chemistry teachers need to include this amalgam of representation in their instruction, and make the connections overtly.

The explanations that chemistry instructors use to describe chemical characteristics and interactions must be student friendly and compatible with the student's existing knowledge base (Treagust & Harrison, 1999). These instructor explanations must connect the how (what is happening) with the why (the reason it is happening) of knowing (Treagust et al., 2003). According to Treagust et al. (2003), there are five most common types of explanations that chemistry teachers use, that of analogical, anthropomorphic, relational, problem-based, and model-based. The first type of explanation, that of analogical, uses something familiar to explain something unfamiliar (and perhaps invisible). The second type of explanation, anthropomorphic, refers to applying a human characteristic to an inanimate object to make it more familiar. The third type is relational, when a personal experience of the learner is used to explain a phenomenon. The fourth type of explanation is problem-based, which is an explanation demonstrated via solving of a problem. The last type of explanation is model based, using a scientific model (that is either given to or developed by the learner) to explain an observation.

Understanding chemistry relies on making sense of the invisible and untouchable, because chemistry exists at the molecular level and in not directly perceivable. Chemistry is a field of study that is inherently representational or symbolic (Kozma & Russell, 1997). The majority of chemistry teachers focus on the symbolic representation during their discussions with students (Lewthwaite & Wiebe, 2010). In addition, chemistry teachers do not integrate the three representations in their discussions, and often switch between the different modes without highlighting their interconnectedness (Gabel, 1999). Teachers often assume that students can easily transfer from one level to another (Johnstone, 1982). The student may not follow the transition or understand differences, leading to confusion and frustration. Students who have limited understanding of the changes that occur at the particulate level during chemical reactions do not know that they must strive for this particulate level understanding, and instead have a tendency to memorize chemical equations without understanding the macroscopic and microscopic significance of the symbols they use (Chandrasegaran, Treagust, & Mocerino, 2008).

Research has shown that chemical understanding is improved by incorporating the particulate nature of matter in instruction (Gabel, 1993; Pickering, 1990; Sanger, 2000). This inclusion helps students make the connection between the microscopic, macroscopic, and symbolic representations used by chemists. By drawing attention and describing each mode in context, chemistry learners are assisted with the difficult formal thought concepts necessary for chemical understanding (Gilbert, 2005; Gilbert & Treagust, 2008; Hoffman & Lazlo, 1991, 2001). Familiarity with the interconnected nature of these representational systems, also referred to as integrated conceptual understandings (Krajcik, 1991), are important for a thorough understanding of chemistry. In comparing the perceptions of experts and novices on a variety of chemical representations, novices used only one form of representation, and rarely could transform to other forms, whereas the experts transformed easily (Kozma & Russell, 1997).

Tetrahedral Modification

An additional dimension to the above model was suggested by Mahaffy (2006), who advocated creating a tetrahedral shape for chemistry instruction, rather than the trigonal planar (molecular geometry metaphor) representation described by Johnstone (1991). The fourth representation and dimension that needs to be added to chemistry instruction is the human element, that of effects of chemistry on humans in contemporary applications and societal issues. According to this representation, students should be encouraged to study the origins of chemistry via historical research of people and discoveries throughout all cultures. Without this important grounding in the human element, there will be insufficient understanding of the effects of chemistry on the human race. This extension won Mahaffy the Chemical Institute of Canada Union Carbide Award for contributions to chemical education, and is now a prominent topic of current research in the field (Ardac & Akaygun, 2004; Gilbert, 2005). Canadian public schools are in the process of training high school chemistry teachers in this tetrahedral orientation (Lewthwaite & Wiebe, 2010) to deliver a new curriculum.

This idea of implementing connections in science to the real world and society are not new in science education, and most recently there has been a renewed interest in the incorporation of science in society with the environmental movement. The American Association for the Advancement of Science (1989, 1993) and the U.S. National Research Council (1996) have issued calls for renewed efforts to incorporate socioscience issues into all science curricula. However, a recent survey of the research on using this humanistic orientation towards teaching science was done by Aikenhead (2003) who found a disconnect between teaching philosophy and practice. According to Aikenhead, most teachers agree it is a good idea to include the humanistic perspective, but when asked about implementation, provided many reasons for not being able to do so.

Teachers' reasons for this apparent discrepancy between beliefs and practice include curricular (not enough time) and contextual (uncooperative colleagues or administration) restrictions. Other teachers do not feel it is their professional responsibility to explore the ethics of science (Sadler, Amirshokoohi, Kazempour, & Allspaw, 2006). Witz and Lee (2009) proposed that there also exists a motivation for some science teachers, especially those who teach physics and chemistry that compels them to love physical science as a discipline. Because they have had an experience in their formative years which imbues in them a powerful understanding or vision of the physical world provided by these disciplines, it has a permanent effect on their view of science, and they are more apt to take an objective and factual approach to teaching and learning. This value-free orientation is often difficult to resolve with the humanistic perspective, and is often cited as the reason that teachers adopt a traditional approach. Alternatively, Witz and Lee also documented that the humanistic perspective can be part of teachers' beliefs if they see in science a "higher vision" in which there is a moral, aesthetic or metaphysical connection – a view that it is the responsibility of science to educate and inform decisions that affect humankind. This belief system is more likely to lead to a socio-science orientation and more humanistic perspective in teaching science.

Effect of Modes of Representation on Student Achievement and Learning

It is important for the chemistry learner to think about chemical phenomena using multiple modes of representation, in order to grasp the complexities of the topic. The biggest barrier to this complete understanding is that chemistry instruction occurs predominantly on the most abstract level, the symbolic level (Gabel, 1999). In order to understand the microscopic level that cannot be seen, a learner must be capable of associating the idea of particles interacting with models or analogies. Then, the model created must then be associated with symbols. Finally, the teacher must articulate all levels in instruction and include the anthropomorphic effects in order to assist the students in making the connections and completing their understanding of chemical phenomenon. In order to be experts at chemical understanding, the learner must be able to translate what they see (the how) to the rationale for the event occurring (the why).

Since many of the topics studied in chemistry are abstract and invisible, they are inexplicable without using models, analogies, or metaphors. Evidence that is macroscopic in nature is explained using symbolic means. Unless the connection is made in the mind of the students between what they see and how it might look at the microscopic level, learning becomes difficult. The bridge between what is seen with the symbols used to depict interactions needs to be made via the microscopic model. As a result of having to deal with three levels of representation simultaneously, learners generally experience difficulty in explaining chemical reactions (Gabel, 1998). Students are often not able to translate one representation into another due to their limited conceptual knowledge and poor visual-spatial ability (Keig & Rubba, 1993). Students experience difficulty in understanding the microscopic and symbolic systems of representation because these representations are abstract and cannot be experienced (Ben-Zvi, Eylon, & Silberstein, 1987; Griffiths & Preston, 1992). Research has been done on how chemistry course content affects student achievement (Barker & Miller, 1999; Laverty & McGarvey, 1991; McNeely & Marek, 2003; Nieswandt, 2001; Solomonidou & Stavridow, 2000), but not much has been done on how the mode of representation used affects student understanding and achievement.

Innovations in Resources for Chemistry Learners

Modern chemistry cannot be taught without models (Harrison & Treagust, 1998). Understanding the microscopic and symbolic representations of matter requires some abstraction, often through the development and use of mental models and images (Gabel, 1987). Students must be able to assemble and manipulate models of molecules they are thinking about in order to work through problems on chemical bonding, molecular geometry, polarity, intermolecular forces and even kinetics. Students are required to interpret a variety of representations of chemical bonds (e.g., chemical formulas or ball-and-stick models) and chemical bonding is a topic about which students commonly develop a wide range of alternative conceptions (Coll & Treagust, 2003). Representational competence is a set of skills that allows a person to reflectively use a variety of representations or visualizations, to think about, communicate, and make predictions on chemical phenomenon (Kozma & Russell, 1997, 2005). The ability to comprehend and mentally manipulate chemical configurations is critical to student understanding of the content (Wu & Shah, 2004). Mental models that represent actual particles cannot be understood or learned like content and must be practiced for the learner to become proficient. To support student understanding at the interface of the three modes of representation, the learner's knowledge base must include the ability to translate between the macroscopic, microscopic, and symbolic representations of chemistry; specifically in making meaningful connections between observations of macroscopic phenomena and explanations at the particulate level (Gabel, 1993, 1999; van Driel & Verloop, 2002).

Students who can solve problems that are quantitative in nature using algorithms, are often unsuccessful at answering questions that are particulate in nature (Gabel, 1998; Nakhleh & Mitchell, 1993; Nurrenbern & Pickering, 1987; Smith & Metz, 1996; Zoeller & Lubezky, 1995). The combination of the abstract and dynamic nature of many processes like kinetics, equilibrium or electrochemistry makes them especially difficult to understand. Textbooks and drawings are static in nature, and cannot depict the dynamics of chemistry at the molecular level. Because students have problems visualizing and conceptualizing these types of processes, the use of animations have proven an especially useful type of computer-aided instruction. Strategies that help students visualize atoms, molecules, and ions are among the most successful ways to improve their conceptual understanding of chemistry at the molecular level (Sanger & Badger, 2001).

Computer animations that depict atoms and molecules have only been available to students for the last 10-15 years. Animations have been shown to improve representational competence significantly (Kozma & Russell, 1997) and may assist students in linking the various representations. Computer animations have proven especially useful in assisting female students (Yezierski & Birk, 2006) by clarifying their visualization of molecular-level interactions via the particle model for matter. The use of models in chemistry, particularly the modeling of submicroscopic particles in chemistry seems to result in higher achievement in girls when compared to boys that were not taught using the particle model (Bunce & Gabel, 2002). Computer animations have even been shown to cause conceptual change to occur and assist students in changing previous misconceptions towards more scientifically acceptable views of matter and interaction (Sanger & Greenbowe, 1997). Finally, and probably most important, is that computer animations may help students relate the macro, micro, and symbolic representation levels of chemical entities to each other (Gilbert, de Jong, Justi, Treagust, & van Driel, 2002).

Chapter 3

Methods

Conceptual Framework for Research

As a teacher, I have had multiple and varied professional experiences. First, teaching physical science and mathematics to junior high students for 5 years, then teaching chemistry and mathematics at the high school level for the next 13 years. Finally, I have worked teaching chemistry at the community college level for the last 12 years. I have been a classroom teacher for over 30 years, a department chair, and even an administrator in charge of evaluating other teachers. My education, experience, and professional development give me high self-efficacy as a chemistry instructor; I have learned a lot about what works and what doesn't.

These varied experiences certainly provide useful insight into the context of the profession and culture in which I work. When I set out to do my research, it made sense to use my experience as a backdrop for my goal of determining how the trigonal planar model of chemistry instruction influences student understanding.

I believe, and my review of current research-based literature supports the idea, that more diverse usage of different representational modes increases student understanding. Given my belief that a diverse delivery influences the depth and breadth of student understanding, it was important to observe the teachers and students interacting and their use of different modes of representation during teaching and learning chemistry. I wanted to assess student understanding on a larger scale using a pre- and post-test to determine how students' understanding changed after a semester of General

Chemistry I at the community college level. I also wanted to include student interviews in my analysis, to add more information to my data collection.

Below is a diagram of the influences I believe are at work in the classroom as teaching and learning takes place in the context of General Chemistry I at the community college level. Additionally, I have placed the influences of both student and instructor on this conceptual framework, and included the trigonal planar nature of understanding, as well as how I intended to assess that understanding in my research.

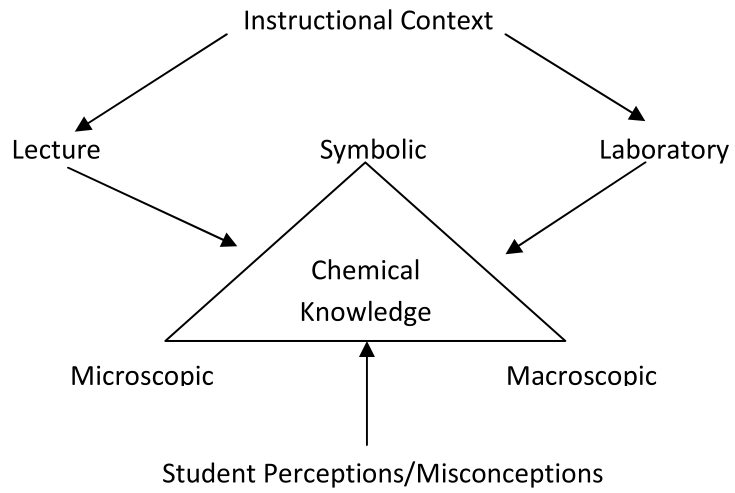

Figure 1. Conceptual framework.

Research Questions

The overriding quantitative questions for this research were:

1. What percentage of the total instructional time in community college chemistry lecture and laboratory is spent using symbolic, macroscopic, or microscopic modes of representation?
    a. How do community college chemistry instructors differ from each other in their use of the three different modes of representation?
    b. Does the mode of representation used vary significantly between the lecture and laboratory according to instructor?
    c. Does the percentage of time spent in the different modes of representation vary according to curricular topic?
2. Does the focus on mode of representation by the instructor influence student achievement, as measured by a change in the Assessment of Basic Chemistry Concepts (ABCC) score (Mulford, 2002)?

Mixed methods (both quantitative and qualitative) were used to answer the following questions:

3. Is there a relationship between instructional use of modes and the student's ability to use evidence as explanation of an observed phenomenon?
4. Is there a relationship between instructional use of modes and the proficiency of the student in describing and representing chemical reactions in macroscopic, microscopic, and symbolic modes?

Overview of Research

Each of the above questions considered as the smallest unit of study the individual class/section of community college General Chemistry I associated with a particular instructor. Since the smallest unit of study was an individual class, the independent variable was the percentage of instructional time spent in each of the three different modes of instruction. The dependent variable, student learning, was measured using both quantitative and qualitative assessments.

Because there were both quantitative and qualitative questions, the research approach was a mixed methods study. Mixed methods were chosen to ensure a comprehensive research experience and make progress at validity through triangulation of data and results. The triangulation of data collected included classroom observations, pre- and post-student assessment, and interviews of both instructors and students – all of which can be used to compare what happens in the classroom with what students are learning.

Research Permissions

Two different Institutional Review Board (IRB) criterions had to be addressed and met in order for the research to begin. The first IRB was for the university system, since I am a PhD candidate and the research originated within the confines of the university. Additionally, IRB approval was needed for the large southwestern community college system in which the research was to be conducted.

Instructors were recruited after both IRB approvals were obtained. Three different community college General Chemistry I instructors agreed to be part of the research. The three instructors were within the same southwestern community college system, so that I could facilitate research within the same semester. Once the instructors agreed to participate, the individual college deans and presidents also had to give permission for the research to take place on their campuses. This approval and recruitment process took place during the spring and summer of 2012. By fall of 2012, all approvals and materials had been prepared, and the research began.

Setting, Student Population, and Instructors

Three different locations of two different colleges within the southwestern community college system were represented in the sampling, where each of the instructors worked as full time residential chemistry faculty. Each of the colleges has approximately the same total population of students (one college simply has two physical locations, approximately 8 miles apart). Within each of the college's surrounding areas there are lower middle to upper middle income-level households. The student population (described later) was relatively homogeneous within the three locations. These colleges were chosen for many factors, including the fact that I had professional relationships with each of the instructors and they were aware of my dissertation research. Additionally, the geographic location of each of the three locations played a part in the choice, since I had to do all the observations at each of the three locations. The three locations were all within an hour's drive from my residence, so that I could perform the observations weekly at each site.

The first college (college I) is in a more established residential area of a centralized Southwest metropolitan area. The college I student community has a lower proportion of Hispanic students (see Table 1), but a higher proportion of Native American students as it is close to the Pima Indian reservation. College I has also been in existence longer; it was established in 1970.

The second college (college II) is 23 miles directly south of the first college. It is in an area that was established more recently and many of the homes are new. College II has more Hispanic and Asian students, and fewer Native American and white students. College II was established in 1999. The comparable demographics on each of the colleges are as follows:

Table1

Racial Composition of Colleges I and II

Race	College I	College II
African American	4.3%	4.9%
American Indian	4.7%	1.7%
Asian	3.7%	6.2%
Hispanic	11.1%	17.5%
White	68.3%	58.4%
Other	7.9%	11.2%

The population studied in this research consisted of students in their first semester of general chemistry at the community college level. The course, General Chemistry I with laboratory, took place during fall semester 2012. General Chemistry I is the first semester of a year-long series of general chemistry lecture and laboratory that most pre-professional medical, scientific, and engineering degree programs require as a "gatekeeper" course to continue in the pre-professional curriculum.

For the three instructors in the two colleges, there was a common lecture and laboratory arrangement with regard to scheduling of lecture and laboratory sections. Each of the colleges scheduled a large lecture class (approximately 50-75 students) twice a week for 1.25 hours per class. The student population in these large lectures was broken down into several laboratory sections of about 25 students each. The laboratory periods were once a week for 2.5 hours per meeting. At all three locations, the students attended the course during a 15-week semester, with 150 minutes of lecture instruction per week and 160 minutes of laboratory instruction.

Since all three locations of the two colleges were in the same southwestern community college system, the standardized course competencies were set by the Instructional Council for the community college district and the Articulation Task Force for the state. This standardization is necessary to ensure that students leave the course with a required set of skills contained in these competencies (see Appendix C), which are necessary for success in the subsequent course: General Chemistry II and laboratory.

I observed each chemistry instructor for at least 1 hour during lecture, and 1 hour in laboratory classes each week, for a total observational time of 2 hours per week per instructor, and 6 hours of observation time each week for all instructors. I also recruited student volunteers from the classes I observed. In order to recruit the students, I came to the first laboratory meeting of the semester and explained my research to the students. I told them that I wanted to pre- and post-test as many students as possible, and offered candy bars or composition books as a small incentive to take the assessments (see recruitment script and informed consent forms, Appendix D). One hundred and seven students from the three classes volunteered to take the pre-test, and a total of 79 of those students were still enrolled and volunteered to be assessed during the post-assessment, which was administered during the last week of class. The attrition in pre- and post-test volunteers was due to students dropping the course rather than from refusing to take the post-assessment.

I also interviewed the students and instructors to get a more in-depth perspective of each point of view. Instructor interviews took place at the outset of the semester, and the student interviews took place at the close of the semester. To recruit student volunteers for the interview portion of my research, I went to the laboratory section of the courses and made an announcement that I was looking for student volunteers to be interviewed. I told students the interview would take about an hour and offered them an incentive of $10.00 in cash to take part. I was able to get 13 students to volunteer to be interviewed at the end of the semester. Of the 13 students who volunteered and were interviewed in depth at the end of the course, 12 of the interviews were used for comparison.

Methods and Instruments

Quantitative and qualitative methods were necessary to answer the questions posed in this research. These methods were categorized into three different areas of data collection: classroom observations, large-scale student assessment, and small-scale student and instructor interviews. By collecting data from multiple sources within the setting for research, a triangulation of results could be made.

Classroom observations. To understand the complex interactions involved in teaching and learning that occur in an individual chemistry classroom, and how those interactions influence student understanding, I needed to document instructional context within each of the three classes. Although curriculum content is outlined by district and state course competencies, the depth and delivery are entirely up to the instructor. The instructor's practice is influenced by many factors, including their own educational background, experience, and beliefs.

When teaching chemistry, there are many ways to approach the curriculum, and evidence suggests that teachers should give explicit attention to addressing the different modes of representation. Using multiple modes of representation in instruction supports student learning in chemistry (Ardac & Akaygun, 2004; Gilbert, 2005). Specifically, images of the microscopic particles and their interactions provide an important interactive quality, showing the relationship between the parts represented (Osborne & Wittrock, 1985) by the symbolic equation, making the connection between the modes of microscopic and symbolic. Johnstone (1991) and Gabel (1999) found through their observations that most chemistry teachers focus primarily on the symbolic mode of representation and, if they do use other modes, do not overtly make the connection between modes to the students.

A teacher self-reporting survey (Lewthwaite & Wiebe, 2010) exists to determine mode of instruction used most often, as well as a student survey of modes used by their teachers, but direct observation by an expert is preferable to standardize criteria from surveys. Also, by observing each of the teachers and classes weekly over the course of an entire semester, I accrued a more representative sample of the complex interactions involved in teaching and learning chemistry, especially as these interactions were focused on a particular chemistry topic. An instrument to quantify and document the modes of instruction used by chemistry teachers as instruction is delivered does not exist, so I developed such an instrument for this research.

Classroom observation instrument. I created the first instrument to evaluate mode of representation used during instruction and in conversations that teachers have with students. I used this instrument during classroom observations in order to document the mode of representation used during instruction. The observation instrument I created is called the Classroom Observation Rubric (COR; see Appendix A) and was developed specifically for this research project to keep track of the mode of representation used by the instructor during classroom observations.

The COR categorizes the mode of representation used in teacher-student discussions into three categories: symbolic, microscopic, and macroscopic, and documents this usage in 10 minute increments of time. In addition to documenting the mode of representation, the COR allows for notation of explanations used by the instructor, as well as topical content-related notes. Organization of observational data using the COR was necessary so the modes of representation used could be documented quantitatively to determine how much time the instructor spent in each of the three modes of representation. By classifying subjective observations into categories of mode and recording this mode in 10-minute time frames, I created the COR to quantify a qualitative student experience.

By creating guidelines for the way that observations were done in the chemistry classroom, and a rubric for recording these observations, a quantifiable method for recording mode of representation observed was created. The same rubric and method were used for all classroom observations, so the observation data were reliable with regard to collection methodology for observations. Reliability of the instrument was ensured since the COR allowed consistency in observation both between instructors and over time. Additionally, I collected data from the same population of teachers and students, within the same semester, so threats to the validity of the conclusions were decreased (Creswell & Plano-Clark, 2007).

Classroom observations using COR. During fall semester of 2012, the three instructors were observed approximately once a week, for 1 hour in lecture and 1 hour of laboratory instruction. These observations were done over the 15 week time frame during fall semester 2012 and included 10-12 observations of each instructor. By observing each instructor as frequently as possible and over the course of an entire semester, a fair and representative sampling of their overall instruction was obtained.

During each of the classroom observations, the COR was used to document the mode of instruction used during classroom discussions and teaching/learning activities. The heading of the COR was used to keep track of which instructor was observed, the school, the date and time; and if I was observing a lecture or a laboratory. As the instructional session progressed, I observed in a passive capacity at the back of the room so I would not interrupt the natural flow of teaching/learning. By remaining unobtrusive, threats to the validity of the observation data were decreased. Instructors were not informed which day during a particular week to expect the observations, and they often expressed surprise because I had blended into the class so well and had not drawn the attention of the students or the instructor. Utilization of the COR instrument did not involve any overt participation by anyone other than the observer, and since many students use their computers to take notes, it simply looked as if I was another student.

The primary mode of representation used during each 10-minute increment of the observation period was documented by an entry in one of three columns on the COR. The headings over the three columns were: Symbolic, Microscopic, and Macroscopic. The entry included notes on the topic being discussed. Within this column, a notation using consecutive numerical values was used to indicate which mode was used first, second, etc., as well as how much time was spent in that particular mode of representation.

If the instructor being observed used the symbolic mode of representation first for a total of 3 minutes, I would indicate it on the data table by using the notation 1- in the Symbolic column in the first time frame (0-10 min.), then record the topic. At the end of this notation, I would also record time spent (3 min.) after the abbreviated description. A more detailed description of the instruction that transpired would also appear in the Notes column. If the instructor used multiple modes within a 10-min. increment (i.e., using all three modes), notations of 2a-, 2b-, and 2c- would be used in the respective columns for mode, depending upon which mode was used first/second/third in this period. Minutes spent would be recorded in each mode column, after the abbreviated notes. Again, more detailed notes regarding the example would be recorded in the Notes section. If the instructor then used an additional example in the symbolic mode, still within the first 10 minutes of instruction, a notation of 3- would indicate this last example in the symbolic mode column along with a brief topic description, and a more detailed description would appear in the Notes column. This procedure continued until the observation was complete.

Table 2

Classroom Observation Rubric for Lecture/Laboratory Observations

Instructor: ________________ Instructor C ______________________
School: __________________ College II________________________
Time/Date: 830-940/9-26-12

Time Frame	Symbolic	Microscopic	Macroscopic	Topic/Notes/Explanation
0-10 min. 930-940	1-Equations for SR rxns. 3 min. 2c-animation 1 min. 3-Equation of copper and silver nitrate is written, using an accounting method to keep track of definitions and compounds in the equation. 4 min.	2b-animation 1 min.	2a-animation 1 min.	Equations for SR reactions, to show examples of different reactants/products. Animation of SR in solution starts with macroscopic (beakers with colored solutions). Animation shows the microscopic representation of SR reactions, including ions and charges as they change. After the animated reaction, there is text explanation, accompanied by a balanced reaction. Instructor writes symbolic rep. of balanced reaction between solid copper and aqueous silver nitrate. $Cu(s) + 2AgNO_{3(aq)} \rightarrow 2\ Ag_{(s)} + Cu(NO_3)_{2(aq)}$ Element ionic cmpd. Element ionic cmp No yes no yes No yes no yes The first row is: what are they? Second row: Are they soluble? Third row: Do I write as ions? Problem-based explanations.

An example of the COR with 10 minutes' worth of data, as described above, can be seen in Table 2. Using the COR in this way provided the opportunity to record both the mode/order of representation used, how long it was used, and the topic being discussed. All data was recorded electronically so as to facilitate quick capture as instruction progressed and permanent recording of observations.

Fidelity/reliability of application using the COR. The fidelity of the observation protocol based on appropriate application of the COR instrument was maintained in multiple ways. Coherence of all observations was ensured by utilizing the same instrument (the COR), which was used by the same observer, in the same way, for all observations. This procedure served to improve the overall reliability of the research. Abbreviation codes were noted at the bottom of the COR to ensure easier reference and proper coding during observation periods. Finally, the COR was used only during teaching activities; activities that were not instructional in nature (taking roll, administrative announcements and scheduling changes, etc.) were not included in the observation.

Validity of the COR. The overarching construct validity of the COR was due to an exhaustive review of applicable literature from chemistry education research done previously as it pertains to the construct of the trigonal planar mode of instruction. The simultaneous use of macroscopic, microscopic and symbolic representations has been shown to reduce students' alternative conceptions in chemical concepts (Russell et al., 1997). Since I wanted to determine how the time spent in mode of instruction influenced student achievement, I needed to be able to identify the mode of instruction used during teaching activities as they occurred. Johnstone's (1991) definitions of what should be included in each mode were initially simplistic, and have been refined and added to by others (Gabel, 1999; Gilbert, 2005; Gilbert & Treagust, 2008; Mahaffy, 2006).

The symbolic mode, which is used most often by chemistry teachers (Gabel, 1999; Johnstone, 1991) includes the symbols for the elements as they represent chemical compounds, equations, calculations, data and graphical representations of changes in data, including graphs or algorithms. The microscopic mode, which has been shown in many studies (Ardac & Akaygun, 2004; Bunce & Gabel, 2002) to assist learners in their conceptual understanding of chemical phenomena, includes molecular-level representations and animations that support the atomic-level interactions going on during a chemical reaction. Potential to use this mode has increased dramatically in recent years due to the availability of computer animations. This mode of representation can also include manipulatives like molecular models. With regard to the macroscopic mode of representation, things that can be seen or felt with one of the senses or that are tangible and measurable like color or temperature change or smell, chemical demonstrations are a good way to communicate information. In fact, the macroscopic mode is used most often in lab, where the student is supposed to connect what they see (macroscopic) to the microscopic happenings of the chemical reaction, and then convey this information using symbolic means in a laboratory report. Using these definitions and classifications, I constructed the COR to ensure that each mode of representation used during instruction was documented in terms of time spent, as well as sequential delivery.

Part of the construct validity of the COR was content validity. The content validity of the COR instrument can be determined by the question: Is what is being measured using the instrument important to research? In this case, the COR was used (in comparison to other measures) to evaluate all but one of the seven questions posed in this research, since each of the questions relates time spent in mode of instruction to something else. The COR was used to quantify the time spent in mode of instruction since it classified the mode being used in 10-minute increments. The time spent in mode of instruction can be carefully documented, in real time, as the lesson unfolds and communication takes place between teacher and student. The COR therefore has content validity at least in the context of this research.

As an additional part of the construct validity, the COR certainly had ecological validity since observations were done in multiple, actual, college chemistry classrooms, over the course of an entire semester. No treatment or interventions were used, and the natural course of events that took place within each classroom was not changed in any way. Since I maintained a level of anonymity during the observations, the setting was not disrupted significantly by my presence. The setting not only approximated the real world, it was the actual world of chemistry teaching and learning.

Student assessment. In order to measure student comprehension of chemistry concepts, I assessed the larger population of students using a pre- and post-test of chemical concepts, and interviewed a smaller population of students, drawn from the larger population, at the end of the semester. Two instruments were used to gather data from the population in two different ways, quantitatively with the pre- and post-assessment, and more qualitatively using an interview protocol.

I searched for and found an appropriate instrument to measure student understanding (and misconceptions) in chemistry, which I used as pre- and post-test for the larger student population (n = 79). This instrument was the Assessment of Basic Chemistry Concepts (ABCC). Finding an appropriate interview protocol was not as easy, and one had to be developed to tailor to the specific goals set forth in the context of research.

Written assessment instrument. A written pre- and post-test was used to evaluate student knowledge and change in knowledge before and after instruction. The instrument used to assess student understanding (the dependent variable) objectively was the ABCC, an assessment based on the Chemical Concepts Inventory developed by Doug Milford in 2002 (Appendix D). This test has gone through several modifications since 2009; the most recent iteration, released in 2011, was used for this research. This test consists of 27 multiple-choice questions, several of which were paired to reflect the first part of the question asking about a chemical or physical effect, and the second question of the pair asks for a reason for the observed effect. An additional 3 questions were added to this bank of 27 questions, and were taken from the web site sponsored by the American Association for the Advancement of Science Project 2061. This website is free, and includes available assessment items designed to evaluate students' conceptual understanding and test for common misconceptions.

In this research, it was necessary to find out how well the student understood chemical processes before and after instruction. The ABCC was composed of items that could be directly mapped to one of the three modes of representation, and the additional three items I added targeted the microscopic connection to a balanced equation. This microscopic connection to the algebraic/formulaic method of balancing an equation was not represented in the ABCC, so the items chosen allowed for insight into this variable. Also, by having a 30-item assessment, a more powerful statistical comparison of the data collected could be made.

Validity of the ABCC. The ABCC has been used in the assessment of different groups of chemistry learners who are similar in many respects to my target population: the first semester general chemistry community college student. By using an assessment that has been standardized by a similar population (in this case the first year high school chemistry student), construct validity was ensured.

Using the ABCC, the COR, and the student interviews also helped establish convergent validity between the quantitative COR used during classroom observation and quantitative pre- and post-testing scores of the ABCC, as well the qualitative student interviews. Using all of these measures to answer the questions posed in this research improved convergent validity of the conclusions. These three data sources were used to compare variables (teacher use of mode of instruction and student performance) and provided the connection between variables by allowing triangulation of results.

My target population for this large-scale assessment was students who had the same instructor (one of three instructors who were part of this study) for both the lecture and the laboratory portion of the course. This restriction to the student population was initiated to create a control in the exposure students had to the different modes of representation: a homogeneous exposure to mode by instructor. Additionally, time to test students was difficult to schedule, as two of the three instructors did not want to use class (lecture) time to pre- and post-test the students and instead preferred to have me assess their students during the laboratory portion of the course, when there was more time.

Using the ABCC to assess student knowledge. I came in person to the first laboratory session for each of the instructors and explained my research to a total of five different sections of laboratory students, one lab section from Instructor A, two lab sections from Instructor B, and two lab sections from instructor C. I asked for student volunteers to take the pre-assessment, and offered a candy bar or composition book as incentive and small payment for their time. Students who volunteered were asked to sign a consent form that explained my research further (see IRB documentation). Once they had signed the consent form, they were given the assessment (ABCC) and a Scantron answer sheet to record their responses. Each of the students was assigned a random 5 digit number to use on their answer sheets, and a key of student names and random numbers was created so that no assessment data were associated with individual student names. Once the research was complete, this list was destroyed. Most students completed the assessment in 30-45 minutes. This same protocol for pre- and post-testing was used during the last laboratory session for all three instructors.

Student Interviews

Since the focus of this research is on student learning and achievement, the student voice was crucial to describe the very individualized process involved in learning chemistry. Interviewing students is a more qualitative measure of student understanding, and allows a more in depth insight into the mind of the student. Osborne and Cosgrove (1983) interviewed students of all ages and uncovered one of the most common (and difficult to dispel) misconceptions regarding boiling water, that the hydrogen and oxygen dissociate upon boiling. In fact, Bodner (1991) interviewed graduate students who had majored in chemistry, and some (~20%) still held onto these misconceptions about boiling water. Kakhleh (1992) interviewed eleventh grade chemistry students about particles in weak/strong acids and bases to determine knowledge about molecular level interactions during complex interactions like equilibrium. Krajcik (2012) interviewed ninth grade students and asked them to draw how the air in a flask would appear if they could see it through a very powerful microscope. Even at the university level Cros et al. (1990) interviewed first year chemistry students about their conceptions of atoms and molecules. All of these interviews uncovered student understanding and misconceptions that the authors had not considered prior to the interviews. My interviews had to ensure that I evaluated each student's knowledge and ability to communicate in the three different modes of representation.

I created an interview protocol to delve into the ability of the general chemistry student to communicate her or his knowledge of chemical phenomenon using the three modes of representation. Since these student interviews targeted revealing differences in how the individual utilized modes of representation, I had to get each individual to use all three modes during the interview, and then evaluate the responses according to a rubric. I decided to use demonstration of chemical phenomenon and a questioning strategy to understand each student's perspective on the macroscopic, microscopic, and symbolic modes of representation of chemical phenomenon.

An overriding topic throughout all chemistry courses is the change that matter undergoes when a chemical reaction occurs. Chemists and chemistry students are trained to use visual cues to detect a chemical reaction, and these visual cues are the basis for much microscopic interpretation and symbolic communications. Two common types of reactions that students learn about in General Chemistry I are redox (oxidation-reduction) reactions, and metathesis (double replacement) reactions. Since these are two large categories of chemical reactions in the course, and the appearance and change in appearance of reagents during these types of chemical change are indicative of a particular type of reaction, I decided to use examples of redox and metathesis reactions as the basis for the demonstrations I showed the students. Redox and metathesis reactions are very commonly seen in the laboratory associated with this course, so students would have seen examples of each in lab.

Prior to showing the students the two demonstrations of a chemical phenomenon, I wrote the names for the reagents involved in the demonstration on the white board in the room. After viewing a demonstration of the chemical reaction, I asked the student interviewee to represent that reaction using all three modes of representation: macroscopic using words, symbolic using chemical nomenclature in a balanced equation, and microscopic as drawings of the substances involved in the reaction (see Appendix C, Interview Protocol). Using this ordered progression helped the students to scaffold the information from simple to complex, since viewing a chemical reaction while also knowing the names of the reagents, and being able to describe that reaction in words temporally precedes the ability of a student to write a balanced equation or a microscopic representation. The student must know what they are looking at (the identity of the reactants) in order to determine that the identity of the potential products they see are visually produced during the demonstration.

The reliability of the instrument and the interview process was assured by using the exact same process and questions during each interview. The macroscopic first, then symbolic, then microscopic last in ordering of the interview questions helped students to scaffold their knowledge, and the consistency ensured that all interview participants were given the same information, in the same order, which improves reliability. Interviewing allowed for direct focus on the topic of mode of representation, and provided insight into development of the learners' conceptual framework by inference. By asking students to represent what they saw at a descriptive level (using words), at the symbolic level (using nomenclature and symbols specific to the discipline), and at a particulate level (using drawings), the most effective or useful mode of representation for that student could be determined. In addition, individual nuances and errors in chemical understanding were exposed by obtaining a complete description from the learner of what he or she knew, using all three modes of representation.

The instruction of a particular student in the smallest unit of research (the class/section/instructor) was compared to the mastery of the individual student within each mode of representation. By incorporating the student interviews into analysis, triangulation of all data sources (COR, ABCC pre- and post-test scores, and interview products) provided convergent validity.

Rubrics for interview products. To evaluate the proficiency of the student when using the three modes of representation, the student product had to be evaluated according to a common set of standards. Rubrics were created to evaluate two of the three modes of representation that were used by students to communicate what they observed during a chemical reaction. Two of the rubrics were created a priori, based on my own expertise and what I wanted to uncover about the student's knowledge and misconceptions. The third was evaluated a posteriori, once all responses could be evaluated together in an inductive approach.

The first rubric created was the Symbolic Mode Rubric (SMR) to evaluate the product after students observed a demonstration of a chemical reaction and were asked to write a balanced equation that symbolically represented the chemical reaction. The SMR compared the level of student expertise (novice, practicing, or expert) to three important categories of symbolic representation in a balanced equation: that of nomenclature, states of matter, and balancing.

Each of these categories has connections to the level of expertise within the symbolic mode of representation by the student. The first category, nomenclature, provided an opportunity to determine whether the student understood the rules of nomenclature are how they are applied to the individual components of a chemical compound. The second, states of matter, evaluated how the states of matter (solid, liquid, gaseous, and aqueous solution) were represented in the balanced equation. The third, balancing, determined if the students – using their formulas for nomenclature – understood how the Law of Conservation of Matter was applied to a balanced equation.

The criterion that the third category (balancing) evaluated using the student's nomenclature (whether correct or incorrect) was done in order to disconnect the categories. If the students were incorrect in their nomenclature, and their incorrect nomenclature was used to balance the equation; then they could still balance the equation correctly, without getting the nomenclature correct. In this way, the failure or success of one category in the SMR did not influence the failure or success in any other category.

Each of the three categories in this rubric was subdivided into levels of expertise: novice, practicing, and expert. Definitions for each level of expertise were created for classification. Novice scores were assigned a numerical value of 1; practicing scores a value of 2; and expert a value of 3. Table 3 presents the SMR.

The second instrument created was the Microscopic Mode Rubric (MMR). The MMR was used to evaluate the students' microscopic representation of the chemical reaction. The MMR used the same levels of expertise as the SMR, that of novice, practicing, and expert. The categories mirrored the SMR in topic. Where the topic of nomenclature was evaluated in the SMR, the topic of structure of individual particles was evaluated in the MMR.

Table 3

Symbolic Mode Rubric

Level of Expertise\ Portion Evaluated	Nomenclature	States of Matter	Balanced
Expert	Chemical formulas for all reactants and products are correct	States of matter are labeled correctly for all reactants and products	Equation is correctly balanced (using nomenclature of student)
Practicing	Chemical formulas for <50% of reactants and products are correct	States of matter are labeled, one or more crucial component is missing or incorrect	Equation is incorrectly balanced (using nomenclature of student)
Novice	Chemical formulas for >50% of reactants and products are correct	States of matter are not labeled	No attempt at balancing the equation has been made

The structure of the particles that students drew for their microscopic interpretation had to be the same ratio of individual particles that were used in the students' depictions of the symbolic mode for that particle. For example, the second reaction utilized lead (II) nitrate, whose chemical formula is $Pb(NO_3)_2$. If the students used the correct nomenclature for the particle, they should draw the representative particle as consisting of 1 lead monatomic particle and 2 nitrate polyatomic particles, with each of the nitrate polyatomic particles consisting of 1 nitrogen and 3 oxygen atoms.

The second category in both the SMR and the MMR was states of matter. In the SMR, the student had to use a subscript to denote which state of matter, i.e., (s), (l), or (aq) to depict how that state of matter was being represented symbolically. In the MMR, the student had to depict a solid as having a structure with particles touching each other and a liquid as particles that were touching each other or were suspended in a matrix of water (as in an aqueous solution). The topic of balancing in the SMR was reflected by the category of Law of Conservation of Mass in the MMR. The coefficients used by the students in their balanced equations had to be reflected in the drawings the students created to depict the chemical reaction. Numerical values for the level of expertise remained at 1, 2, or 3, corresponding to novice, practicing, and expert respectively. Table 4 presents the MMR

Table 4

Microscopic Mode Rubric

Level of Expertise\Portion Evaluated	Structure of individual particles	Atomic arrangements	Law of Conservation of Mass
Expert	Ratios of atoms in compounds/molecules are reflected in drawing	States of matter for all substances are reflected in drawing	Coefficients in balanced equation are reflected as particles or moles of reactants/products in drawing
Practicing	<50% of ratios for atoms in compounds are reflected in drawing	Some of the states of matter for substances are reflected in drawing	Some of the coefficients in balanced equation reflect moles of reactants/products in drawing
Novice	>50% of ratios for atoms in compounds are reflected in drawing	States of matter are not reflected in drawing	No attempt at depicting moles of reactants and products (coefficients) is made

Student interviews. A recruitment announcement was made using the electronic platform supported by each individual college so that students could volunteer to be interviewed (see Appendix D for the recruitment announcement). An incentive of $10.00

was offered to students for their time volunteering. A total of 13 students volunteered and were interviewed; of those 8 were from Instructor C, 4 came from Instructor A, and only 1 student volunteered to be interviewed from Instructor B. Although it might have been ideal to have interviewed an equal number of students from each of the three instructors, Instructor C had the largest population of students who were part of my original pre- and post-test sample (51% of all the students in my larger sample came from Instructor C, 28% from Instructor B, and 21% from Instructor A), so having the most students volunteer from the largest population made sense.

The populations of the two schools/three sites were not significantly different and were comparable to many other community college populations, so these results could be considered representative of the overall population of community college students of similar composition. The 13 students who volunteered for the interviews represented a similar range of abilities as those who only volunteered for the pre- and post-testing. The grades of these 13 student interviewees were not known (due to FERPA restrictions) but the pre- and post-test scores of each of the 13 student interviewees were available and could be compared to the scores of the overall population of 79 students. The average pre-test score of the n = 13 student interviewee population was 17.4/30 compared to the average for the larger population with n = 79 students at 14.5/30. The average post test score of the 13 student interviewees was 19.1/30 compared to the average post-test score of the larger population of 79 students was 15.4/30. The average change in ABCC score for the interviewee population was +1.7 and the average change for the larger population of 79 was +.9. The population of interviewees as a subset of the larger student population that was pre- and post-tested was not large enough to do any statistical analysis to show significance, but the values of their pre- and post-tests were such that they were deemed similar in range and average.

Each of the interviews comprised of the same questions and prompts (see student interview protocol, below), and the interviews were audio recorded to ensure accurate reporting. In addition to the audio recording, the products that students created during the interviews were photographed for later analysis using the SMR or MMR rubrics created prior to research. The audio recordings of the student interviews were transcribed as well, for later analysis and comparison using a grounded theory approach.

Student interview protocol. During each of the student interviews, the student was seated in a private room which included white board and markers, and a table. The student was informed of what would happen during the interview and that he or she could choose to stop or quit at any time, without penalty. The student was then asked to sign the informed consent form (see IRB file) for the interview, which included permission to audio tape the interview as it occurred, photograph the equations the student wrote on the white board and the diagrams the student drew (also on the white board) during the course of the interview. The student was identified ONLY using the random 5 digit number assigned at the outset of research.

The first part of the interview was an attempt to collect background information on the student and asked questions that had to do with previous college experience, as well as prior chemistry and mathematics coursework and attempts at understanding chemistry outside the classroom and laboratory site under study. Once this background information was collected, the second part of the interview commenced. During the second part of the interview, the student was shown two different chemical reactions. The first reaction was a redox (oxidation-reduction) reaction, and the second was a metathesis reaction; both of these types of reactions are covered in first semester general chemistry.

The first reaction's reagents were shown to the student interviewee initially, and consisted of a piece of zinc metal in the form of a small silver bar of zinc, and an aqueous solution of copper (II) sulfate, which was blue in color and transparent. The interviewee was allowed to hold the metal, and the copper sulfate solution was placed in a test tube for closer examination by the student. The names of both of the chemical reagents used in this reaction, zinc and copper II sulfate, were written on the white board in the interview room. Once the interviewee was satisfied with examination of the reagents, I asked the student to place the zinc metal into the test tube. Immediately, the metal began to be coated with a thin layer of copper metal, and as the reaction progressed, more copper was produced as a precipitate, and the solution became less blue in color. The student interviewee was shown a test tube with the same reagents in it, but one which had been allowed to react for at least an hour prior to the interview. The student was informed that the reagents in the second test tube had been added together one hour prior. This second test tube could be compared to the test tube in which the student witnessed the reagents being added together, so that a comparison could be made of how the reaction progressed to completion. Once satisfied with the visual example and comparison, the student was asked the following question: "Please describe, using as many chemistry terms as you can, what you just observed."

This question was an attempt to determine the student's macroscopic understanding. I took notes on the interviewees' responses and physical demeanors as they spoke. Additionally, the entire interview was audio taped for later transcription. These verbal responses represented the macroscopic interpretation and mode of representation by the student.

There was no rubric created prior to research to analyze this verbal response and macroscopic description, since the responses were expected to vary significantly. Instead, a grounded theory approach was applied after all interviews had taken place to look for commonalities and differences in students' verbal responses.

The second question asked about the reaction was the following: "Now, can you write a balanced equation for the reaction you just observed and described?"

This second question was asked in an attempt to quantify and measure the depth of student understanding using the symbolic mode of representation. The student was provided with a periodic table for this portion of the interview to use to write the correct nomenclature for the reactants and products. The white board and dry erase markers were also made available (as mentioned previously, the names of the reagents were written on the white board) so that the student interviewee could write the balanced chemical equation on the white board. I observed the student's mannerisms while writing the equation and if/when the periodic table was consulted, and recorded my observations. Additionally, some of the students "talked through" the process as they were working on writing the balanced equation; the audio recorder was left on during the whole process to capture any verbalizations. I also noted when and how many times the student erased work and/or revised the equation. After the student finished writing the balanced chemical equation on the white board, a photograph of the final balanced equation was taken in order to record the student product for later analysis using the SMR.

The third (and last) question asked about the reaction was: “Using the balanced chemical equation you have just written, please draw a microscopic representation of the reaction. What would the reactants and products look like if YOU were the size of an atom, and could watch the reaction?”

This last question was my attempt at documenting and measuring how well the students understood the microscopic mode of representation via their drawings of what the atoms/molecules looked before the reaction, and how the structure of the products was different than the original reactants. As the students drew their molecules, I took note of any conversation that occurred and whether they changed or modified their drawings as they worked. The white board was still available during this portion of the interview, and the original symbolic balanced equation the student had created remained on the board from the previous question. Most of the student interviewees referred to the original equation to assist in creating their microscopic representation of the reaction. Once the student had created a microscopic representation of the reaction, a photograph was taken to be used later when evaluating the student’s response using the MMR.

These student interviews targeted the factors that may influence how useful the different modes of representation are for the individual student. Since the focus of this research is on student learning and achievement, the student voice is crucial to describe the very individualized process involved in learning chemistry. Interviewing allowed for direct focus on the topic of mode of representation, and provided insight into development of the learner's conceptual framework by inference. By asking students to verbalize how they would represent what they see at a descriptive level (using words), at the symbolic level (using nomenclature and symbols specific to the discipline), and at a particulate level (using drawings), the most effective or useful mode of representation for that student was determined. In addition, the individual nuances and errors in chemical understanding were exposed by obtaining a complete description from the learners of what they knew, using all three modes of representation. In this way, the instruction the student receives within the smallest unit of research (the individual class/section/instructor) can be compared to how well the individual student is able to utilize each mode of representation.

Instructor Interviews

In order to better understand the instructors backgrounds and experiences that might influence their teaching practice, I interviewed all three instructors. During these interviews (see teacher interview questions, Appendix D) I was able to find out about their education, teaching history and personal philosophy of teaching. These interviews were done after the semester was over and took approximately 1 hour each.

Descriptive Statistics

After all data were collected, a preliminary analysis using descriptive statistics was done. These descriptive statistics were used to plot graphs to look for trends in the data, and these graphs provided information I used to determine more appropriate in-depth statistical analysis. Below is a description of the process of evaluating the data collected during research, both simple and descriptive statistics.

Classroom observation data analysis. Raw numbers gathered by the COR for minutes in mode of representation were analyzed using chi square analysis. Total minutes in each mode by instructor were determined over all observations done during the 15 week period. A chi square analysis was performed on these summed values, in order to determine if the null hypothesis was true. There was no difference in the time spent in each mode of instruction between instructors.

I wanted to see if the time spent in each mode of representation varied significantly between instructors in the lecture, and then again in the laboratory, independent of each other. Each of the chi square analysis (for lecture vs. laboratory) was 3 X 3, with the three instructors as the independent variable and the three modes of representation (symbolic, microscopic, and macroscopic) as the dependent variable. This gave a degree of freedom of 4 (n - 1 X n - 1), and specified a confidence of 95% (p = .05), the chi square value was determined to be 9.49 or greater for a significant difference to be apparent between the instructors in terms of time spent in each mode of instruction.

After the statistical analysis of time spent in the different modes using chi square, I looked at the COR data in a more subjective and interpretive way, using simple statistics. In order to compare the instructional time spent in mode by date, the classroom observation data was turned into a percentage of time each instructor spent in the three different modes of representation for each observation (by date), as well as an overall percentage time in the different modes of representation by instructor. To determine the percentage of time in mode by date, the 10-minute increments noted in the COR were used to determine the total minutes spent in each mode of representation during that particular observation, by instructor. The total minutes spent in each mode were divided by the total minutes spent in all modes (during a particular lesson) to determine the percentage time spent in each mode, by date. This information was graphed with date as the independent variable and percentage of time spent in mode of instruction as the dependent variable to look for trends in the data by date, topic, and instructor, as well as any apparent trends that might emerge.

Using the observation data above (percentage of time spent in each mode by date), a 3 X 12 within subjects ANOVA was also performed on the data collected from observations of teachers during the lecture portion of their courses. The first factor was mode of representation. Mode of representation had three levels, macroscopic, microscopic, and symbolic. The second factor was the date of observation, which had 12 individual dates, or score sets, for each of the instructors. The dependent variable was the percentage of time spent in each mode of representation.

Mode of representation during the laboratory was also observed, with simple and descriptive statistics performed in the same way as for lecture classroom observation data. These statistics were used to evaluate the differences in lecture versus laboratory instruction, when comparing lecture and laboratory for an individual instructor (to determine if there were differences between the lecture and laboratory instruction of a single teacher). Overall time spent by mode in both the lecture and laboratory were compared using a Welch’s t-test to compare the t-distribution to test the null hypothesis that the two population means were equal (no difference in the mode of representation by venue – lecture vs. laboratory), using a two-tailed test. Each tail of the test was one of the venues for student learning: the lecture vs. the laboratory classrooms.

ABCC score (quantitative) analysis. The pre- and post-testing ABCC data were compiled for all students who took both pre- and post-assessments. Among the five sections of laboratory students available for research, of those who would volunteer, a total population of 107 students took the pre-test, and 79 students retained and took the post-test. Not all students completed the course, and the average attrition over all three instructors was 26%. It was not possible to determine the individual reasons for student attrition due to FERPA restrictions, but the pre-test scores for this population were available. The average pre-test score for retained students was 14.5, and the average pre-test score for those who dropped was 14.7, not significantly different on an assessment of 30 items. For the purposes of retention comparisons, it can be said that a representative sampling of students remained (and took the post-test) of those who had started the course. The instructors agreed that the reasons for dropping the course were varied, including: excessive absences, difficulty with course concepts, poor assessment grades, military deployment, employment scheduling changes, and others.

The pre-assessment served multiple purposes. First, the knowledge (and misconceptions) of chemistry that the individual students brought with them at the outset of the course was determined and used to compare with the student's post-test. Second, a baseline for each individual class/section was compared to the composite to establish any differences between the sections that were apparent at the outset of instruction. If the difference between the students was greater that the difference between the classes, then there would not be any adjustment necessary in the post-test scores using ANCOVA. The reliability of the test, and any apparent differences between the individual student populations was determined using a Cronback's alpha.

A repeated measures, between subjects, factor ANOVA was used to determine the differences in mean scores under the three different conditions (classrooms). Since the different classrooms were the independent variable, the percentage correct was the dependent variable, and it was a between subjects factor since each individual student is only in one classroom.

Again, more descriptive statistical analysis was done. Raw pre- and post-test scores overall were used to calculate average, mean, median, mode and standard deviation for all scores on the ABCC. These same simple statistics were calculated for all pre- and post-test ABCC scores (as groups), and for all pre- and post-test scores of the students who retained (a separate grouping). Finally, each of these simple statistics was calculated for each of the pre- and post-test scores by section/class/instructor.

The pre- and post-test ABCC scores were further segregated by instructor and by sex, to see if these two variables may have influenced results. Once segregated, averages on pre- and post-assessments were calculated by instructor and sex to compare results by gender and instructor and so standard deviation could be considered and compared. Since the population sizes for each of the instructors varied, it was difficult to find an appropriate statistical analysis that would be powerful enough to make conclusions.

An analysis of the individual test question items on the ABCC was also performed to determine which items students missed most dependent on pre- vs. post-assessment, and how the perspectives of the students on the individual assessment items might have changed as a result of instruction. Each of the items on the ABCC was categorized based on its association with the modes of representation, and change in score by mode was determined. This change in score by mode was compared for each instructor, to further respond to the question: Does the focus on mode of representation used by an instructor influence ABCC score? After the chi square statistical analysis of mode of representation, a more descriptive comparison was made between the mode used most often by instructor and the scores on student pre- and post-assessment. This comparison was the start of a triangulation of data points that would eventually include student and instructor interview data.

Student interview (qualitative) data analysis. At the outset of research, I created two rubrics to evaluate the student knowledge of symbolic and microscopic modes (the SMR and MMR, as mentioned earlier). These rubrics were used to evaluate the student responses provided during the interview process and worked well within that context. Since each of the symbolic equations or microscopic drawings that students created during the interview were photographed, the rubrics could be applied later and compared to ensure that consistency was apparent in evaluation. Each symbolic equation the student interviewees created was scored using the SMR, and the microscopic drawings were assessed using the MMR.

The harder part of this evaluation was the subjective qualitative interpretation, especially the verbal description that students proffered, which was part of their macroscopic mode of representation. An inductive approach was used for preliminary analysis of this aspect of the student interviews, to see what commonalities and differences might emerge. This was the most time-consuming aspect of the data analysis, but also the most interesting considering that many other simple statistics had been generated at this point and could be compared to the individual student interviews.

The verbal responses given during the interviews to the macroscopic interpretation of each chemical reaction were analyzed using an inductive approach. This inductive approach allowed for the collected responses to guide analysis, rather than using a theoretical perspective to classify potential responses prior to collection (Erickson, 1986). The goal of this analysis was to determine if the student was making connections between the different modes of representation during the interview process and students were asked the following question: “Please describe, using as many chemistry terms as you can, what you just observed.” To begin this more qualitative analysis, all interview responses to this question were transcribed, and key words/phrases were isolated using a word count for frequency in response to each individual question. A list of most common words/phrases was constructed, and these words were used to determine the context of the sentence/statement in which they appeared. Finally, contingency statements that contained the key words/phrases were analyzed to determine if the student used visual observations (color change, heat evolving, precipitate forming) to justify the description of what was happening at a molecular level (the actual chemical reaction), and the reasons or justification for the reaction (activity of metals, solubility).

Once all the verbal responses were categorized into one of the three categories (novice, practicing, and expert) and assigned a numerical value (1 for novice, 2 for practicing, and 3 for expert) using the V/MMR, their responses to the SMR, MMR, and new V/MMR were compared. A series of Pierson product correlation coefficients were performed on the students' scores using the different instruments from the interviews.

After the statistical analyses comparing SMR, MMR, and V/MMR scores were completed, a broader comparison of the interviewee's ABCC pre- and post-test scores was done. The purpose of this comparison was to see if there was any relationship between the scores on the rubrics obtained by interviewing students and their scores on the written ABCC assessment. The ABCC was deconstructed to categorize the individual questions on this assessment into one of the three modes of representation. Then, the student interviewees' scores on the questions from the ABCC that related to a particular mode could be compared to each of their scores on the SMR, MMR, and V/MMR.

Chapter 4

Results

Data collected were analyzed by source, and consolidated results and analysis will be presented by instrument and context. A brief introduction of the instrument and how it was used will be followed by summaries of data collected, and finally by the simple and descriptive statistics used to evaluate the data. The overall reporting of results will be done first by quantitative evaluation and then qualitative evaluation, following the sequencing of research.

Classroom Observation Data and Analysis

The COR was used to record instructors' teaching activities over the course of the 15-week semester. Each instructor was observed for an hour in the lecture classroom, and another hour in the laboratory every week, for a total observation time of 2 hours per instructor per week. Although there was always a full hour of instruction in the lecture each week, the laboratory did not receive as much direct instruction, due to the format of chemistry labs in general. This format generally included a brief introduction to the lab at hand, instructions on safety and instrumental protocol, and then the students were released from the "teaching" part of the session to actually do the lab. The instructors then generally walked around, facilitating student work and monitoring the safety of the participants.

These classroom observations yielded a total of between 10-12 hours of observation for each teacher by venue (lecture or laboratory), and both venues provided a total observational time of 20-25 hours per instructor; with approximately half of the observational hours done in the lecture, and half done in the laboratory. The raw values (total minutes in each mode, over the course of the entire semester) are shown in Tables 1 and 2 below. All minutes in each mode have been totaled over the entire observational period. Table 5 is a summary of the data collected over the 15-week observational period, for both the lecture and the laboratory.

Table 5

Total Minutes % Time Spent in Mode of Representation by Instructor and Venue

Instructor	Lecture min./ % time Symb.	Lecture min./ % time Micro.	Lecture min./ % time Macro.	Lab min./ % time Symb.	Lab min./ % time Micro.	Lab min./ % time Macro.
A	443/67	122/18	95/14	50/36	1/1	89/63
B	416/68	99/16	99/16	93/57	13/8	56/35
C	388/73	70/13	70/13	65/33	17/9	117/59

Simple descriptive statistics were calculated using percentages based on values contained in Table 5 above. Table 6 below summarizes the values of those descriptive statistics for each instructor and mode of representation.

Table 6

Mean and Standard Deviation for Time in Mode of Representation by Instructor

Instructor	Symbolic mode	Microscopic mode	Macroscopic mode
A	M = 67.5, SD = 22.56	M = 20.7, SD = 20.47	M = 11.8, SD = 6.14
B	M = 65.6, SD = 13.96	M = 16.3, SD = 15.60	M = 17.2, SD = 3.51
C	M = 74.7, SD = 11.49	M = 13.2, SD = 12.22	M = 12.0, SD = 8.54

A 3 X 3 chi square analysis was performed on the values in Table 5, with the 3 different instructors as the independent variable, and total minutes in mode of representation (symbolic, microscopic, and macroscopic) as the dependent variable. I wanted to see if the instructors were significantly different in their use of mode of representation during lecture activities. With 4 degrees of freedom (n - 1)(n - 1) and specifying a confidence level of 95% ($p = .05$), a chi square value of 9.49 or larger was necessary for a significant difference to be apparent between the instructors in terms of their time spent in each mode of instruction for the lecture, and again for the laboratory portion of the course.

The chi square value for the comparison of lecture time between instructors was calculated to be 15.37. A value of 15.37 for chi square affirms a significant difference between the instructors in their use of mode of instruction, if all instructional time (over the 15-week observational period) is taken as a whole. Chi square statistical analysis was performed on observational time for the minutes spent in mode of representation in the laboratory venue, with an even larger chi square value determined to be 40.2, which shows that the teaching mode differed significantly between instructors in the laboratory context as well, if instruction in the lab is taken as a whole over the 15-week observational period. Looking deeper into the cells that comprise the chi square analysis for lecture and laboratory, the values for the individual cells $[(O-E)^2/E]$ can be summarized in Table 7.

Table 7

Chi Square Cells for Lecture and Laboratory Venue by Instructor

Instructor	Symbolic mode lecture	Micro. mode lecture	Macro. mode lecture	Symbolic mode lab	Micro. mode lab	Macro. mode lab
A	.27	2.40	.30	1.10	7.00	3.50
B	.67	.04	4.20	10.10	.90	10.00
C	2.30	2.30	2.90	3.90	2.10	1.60

Looking at the individual cells that make up the chi square analysis is helpful, to see which cells provide the greatest values, which is an indication of anomalous scores and the location of differences among the instructors. In the chi square analysis of lecture, Instructor C contributed most to the large x^2 value, since all cells for Instructor C had high values. Instructor B had the highest value of any of the individual cells, in macroscopic mode. The individual cells in the chi square analysis of laboratory mode of representation, shows Instructor B contributed the highest cell scores, in symbolic and macroscopic modes of representation.

Overall percentage time spent in each mode of representation by instructor was calculated by taking the minutes in each mode, divided by the total minutes in all modes of representation. Percent time in each mode, by instructor, is summarized in Figure 2.

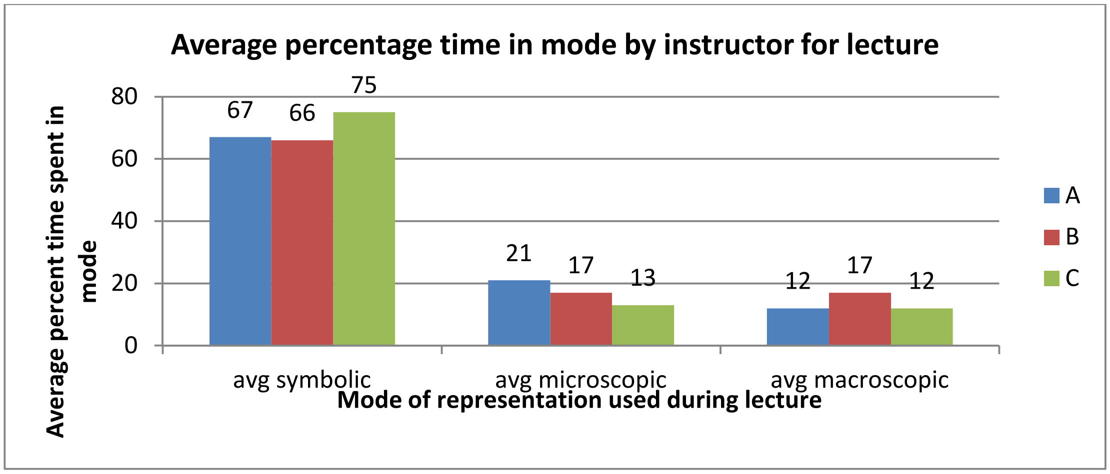

Figure 2. Average percentage time in mode by instructor during lecture.

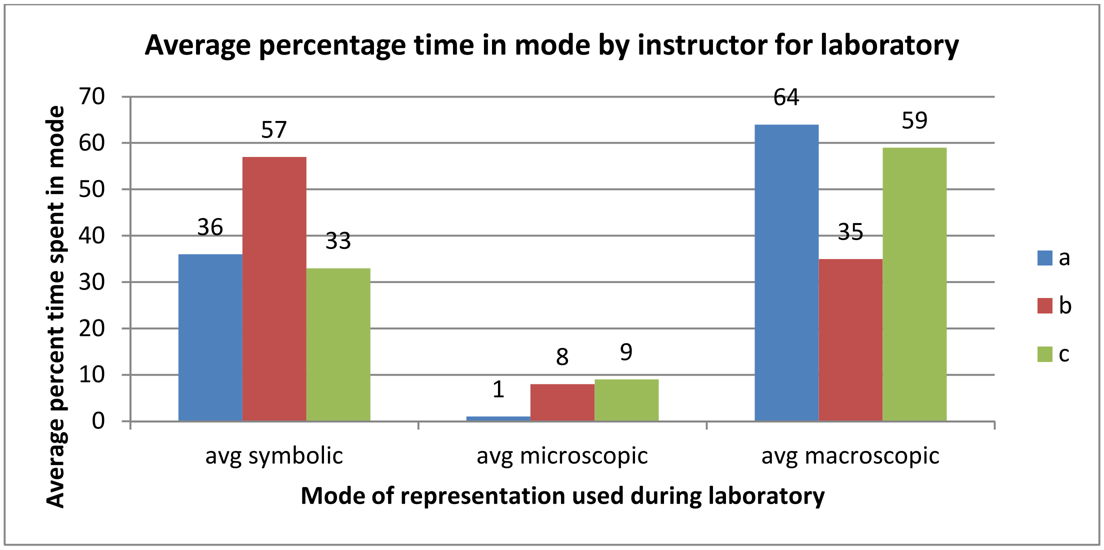

Figure 3. Average percentage time in mode by instructor during laboratory.

Once the percentage of time spent in each mode was determined, an additional statistical analysis was done, this time an ANOVA on the percentage time in instructional mode for each instructor, over time. The raw data/percent time in mode of representation used for the ANOVA analysis is contained in Table 8 and in Figures 4-6. Using the observation data above (percent time spent in each mode by date), a 3 X 12 within subjects ANOVA was performed on the data collected from observations of teachers during the lecture portion of their courses. The first factor was mode of representation, with three levels: macroscopic, microscopic, and symbolic. The second factor was the instructor, with the date of observation having 12 levels for each of the instructors. The dependent variable was the percentage of time spent in each mode of representation.

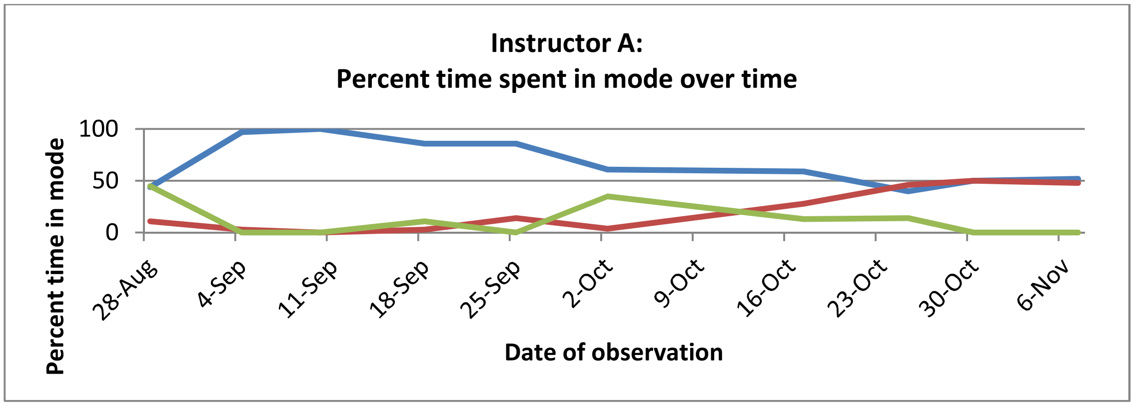

Figure 4. Percentage time spent in mode for Instructor A, over time, in lecture.

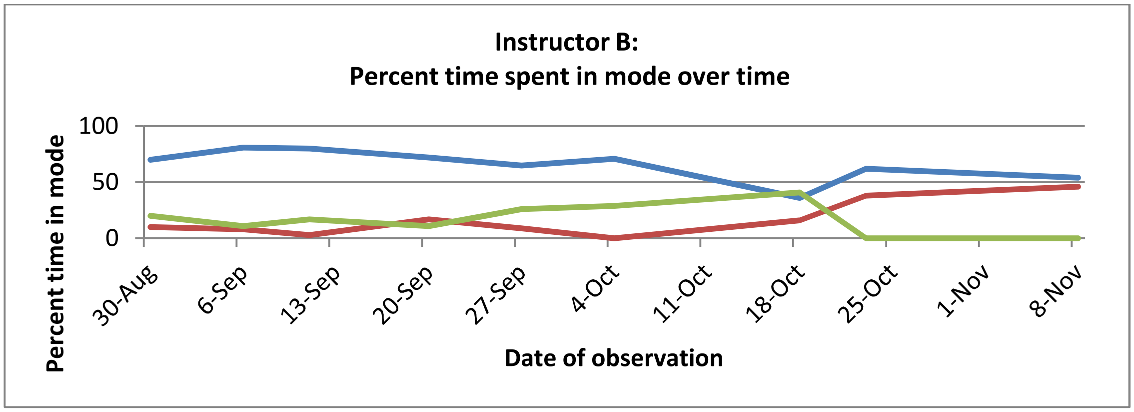

Figure 5. Percentage time spent in mode for Instructor B, over time, in lecture.

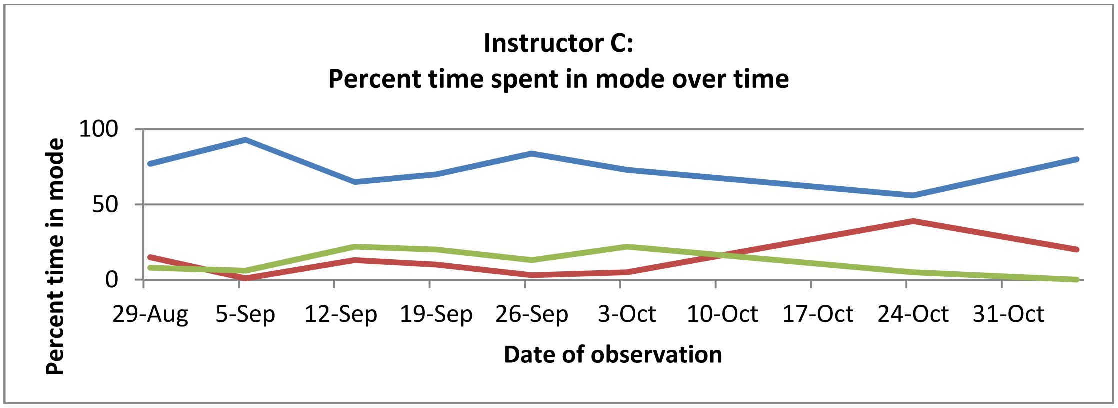

Figure 6. Percentage time spent in mode for Instructor C, over time, in lecture.

Table 8

Minutes/Percent Time in Instructional Mode for Each Instructor by Date in Lecture Venue

Instructor	Date Day-Month	Minutes/percent time in symbolic mode	Minutes/percent time in microscopic mode	Minutes/percent time in macroscopic mode
A	28-Aug	44/44	11/11	45/45
A	4-Sept	58/97	2/3	0/0
A	10-Sept	75/100	0/0	0/0
A	18-Sept	60/86	2/3	8/11
A	25-Sept	43/86	7/14	0/0
A	2-Oct	43/61	2/4	25/35
A	17-Oct	44/59	21/28	10/13
A	25-Oct	20/40	23/46	7/14
A	30-Oct	30/50	30/50	0/0
A	7-Nov	26/52	24/48	0/0
B	30-Aug	49/70	7/10	14/20
B	6-Sept	61/81	6/8	8/11
B	11-Sept	56/80	2/3	12/17
B	20-Sept	51/72	13/17	11/11
B	27-Sept	49/65	7/9	19/26
B	4-Oct	53/71	0/0	22/29
B	18-Oct	25/36	11/16	29/41
B	23-Oct	37/62	23/38	0/0
B	8-Nov	35/54	30/46	0/0
C	29-Aug	50/77	10/15	5/8
C	5-Sept	62/93	1/1	4/6
C	13-Sept	49/65	10/13	16/22
C	19-Sept	49/70	7/10	14/20
C	26-Sept	59/84	2/3	9/13
C	3-Oct	40/73	3/5	12/22
C	24-Oct	39/56	27/39	4/5
C	5-Nov	40/80	10/20	0/0

The means and standard deviations for time in mode of representation as a function of instructor (A, B, or C) are summarized in Table 9. The ANOVA indicates no significant interaction between time spent in symbolic mode of representation and instructor over time: F(2, 21) = 1.60, p = .227; no significant interaction between time spent in microscopic mode of representation and instructor over time: F(2, 21) = 1.57, p = .231; and no significant interaction between time spent in macroscopic mode of representation and instructor over time: F(2, 21) = .75, p = .484. The mean and standard deviation for this data are summarized below.

Table 9

Means and Standard Deviations for Instructional Mode

Instructor	Mode of representation	Mean	SD
A	Symbolic	62	17.7
A	Microscopic	28	20.8
A	Macroscopic	10	12.5
B	Symbolic	65	14.0
B	Microscopic	16	15.6
B	Macroscopic	17	13.5
C	Symbolic	75	11.5
C	Microscopic	13	12.2
C	Macroscopic	12	8.5

ANOVA for each mode shows that the p value is greater than .05 for each category (i.e., mode of instruction), which means there is not a significant difference between instructors in their usage of mode of representation in the lecture, over time.

Student Assessment Data and Analysis

The ABCC was a 30-item assessment used as a pre- and post-test of the larger student population (n = 78) of the three instructors. The ABCC was administered in the laboratory at the outset of the semester, and again within 1 week of the end of the semester. These scores were used in part to evaluate the change in the students' basic chemistry knowledge from the three different instructors.

Before analysis on student achievement could be done, it had to be determined whether the populations of each of the three classes from the three different instructors/college locations were significantly different in their pre-course knowledge of basic chemistry concepts. A 3 X 1 ANOVA was done on the pre-test scores, with the instructor as the independent variable, with three levels from the three different college locations, and the ABCC pre-test score as the dependent variable. The ANOVA was not significant: $F(2,75) = 1.04$, $p = .358$. Since the ANOVA failed to show significance, an ANCOVA as follow up was not necessary. Table 10 is a summary of the simple statistics for the instructors and the students' pre- and post-test scores.

Table 10

Mean and Standard Deviation for Pre- and Post-Test ABCC Scores by Instructor

Statistic	Pre Inst A	Post Inst A	Pre Inst B	Post Inst B	Pre Inst C	Post Inst C
M	46.66	55.00	42.72	45.76	49.82	54.67
SD	19.12	17.21	14.48	15.37	18.75	21.15

The next statistical analysis performed on ABCC pre- and post-test scores was a paired t-test for ABCC scores, using a matched subject design between pre- and post-test scores for each student by instructor. Three paired t-tests were done, one each on the three different populations of students' scores from the three different instructors. This test was done to determine if students knew more at the end of the course in comparison to the outset of the course. The primary question of interest to this analysis is whether the mean difference between the scores on the two assessments (pre- vs. post-test) is significantly different than zero. For our purposes, a 95% confidence level was desired, so $p < .05$ would be considered significant.

The results for Instructor A indicated that the mean of the post-test ABCC scores (M = 55.00, SD = 17.21) was significantly greater than the mean for the pre-test scores (M = 46.44, SD = 19.12), t(15) = 2.86, p = .012 < .05. The 95% confidence interval for the mean difference between the two sets of scores was 2.1 to 14.6.

Results for Instructor B indicated that the mean for the post-test scores (M = 45.76, SD = 15.37) was not significantly greater than the mean for the pre-test scores (M = 42.72, SD = 14.48), t(21) = 1.12, p = .275 > .05. The 95% confidence interval for the mean difference between the two sets of scores was -2.6 to 8.7.

Finally, the results for Instructor C indicated that the mean for the post-test scores (M = 54.67, SD = 21.15) was not significantly greater than the mean for their pre-test scores (M = 49.82, SD = 18.75), t(39) = 1.9, p = .065 > .05. The 95% confidence interval for the mean difference between the two sets of scores was -0.3 to 9.9.

Another comparison of change in score by gender and instructor was made, to see if the sex of the student might influence achievement. The scores by sex of the students was disaggregated and compared by class. All of the classes had a higher percentage of boys than girls, which affected the differences between the values in Table 11 and Table 12. Table 11 shows the percentage breakdown in male versus female students by instructor. An average gain score on the ABCC by sex was determined by averaging all the gains/losses of all students in each instructor’s class, by sex. The values for the average gain/loss by instructor and sex are given in Table 12.

Table 11

Gender Percentage by Instructor/Class

Instructor	Percentage male students	Percentage female students
A	69	31
B	59	41
C	62	38

Table 12

Average Percentage Change in ABCC Score by Sex and Instructor

Sex of student	Percent Change in ABCC Instructor A	Percent Change in ABCC Instructor B	Percent Change in ABCC Instructor C
Male	9.0	7.0	6.3
Female	6.0	1.1	-0.7
Combined (total)	8.3	3.0	4.8

Table 12 shows the percentage improvement on the ABCC by sex and for all students by instructor. The students in Instructor A's class improved on the ABCC the most. In breaking down the achievement of students by sex (Figure 7), it appears that boys made more gains in ABCC score with all three of the instructors. Overall, the girls made much lower gains on ABCC scores, except with Instructor A. The raw point gains by the girls in Instructor A's class were on par with the raw point gains made by the boys in the other two classes (Figure 7).

Analysis of Student Interviews

Twelve students from the original population of the three instructors' students were interviewed at the end of the semester. The 12 interviewees had also taken the pre- and post-ABCC assessments. Of these students who volunteered to be interviewed in the last 2 weeks of the semester, 4 students were from Instructor A, and the remaining 8 students were from Instructor C's class. It was not possible to get any of the students in Instructor B's class to volunteer for the interviews.

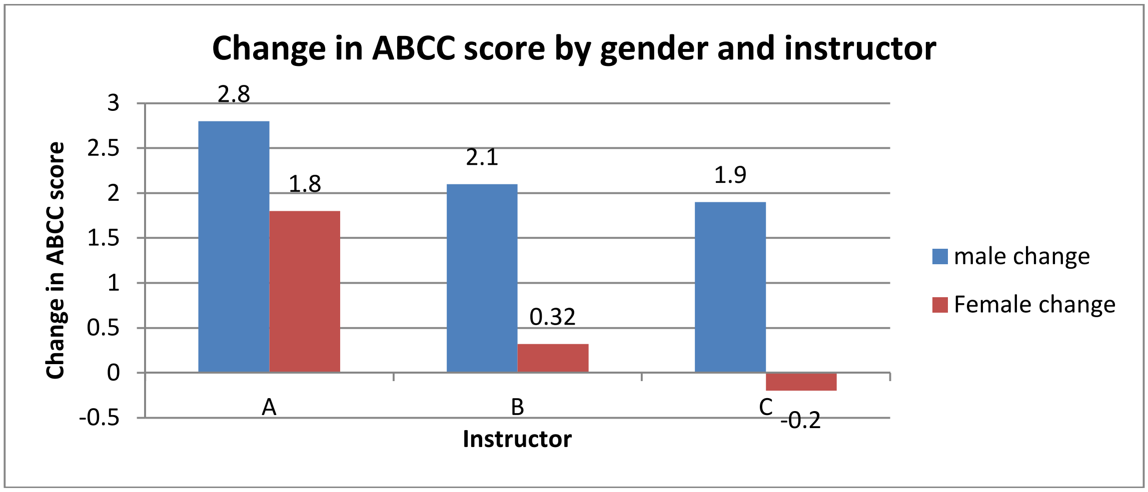

Figure 7. Average raw points gained on ABCC (post-pre) based on gender and instructor.

During the interviews, each of the students was shown two chemical demonstrations: the first of a redox reaction and another of a metathesis reaction. The names of the reagents used during each demonstration were written on the board prior to the demonstration. After the demonstration, the students were asked the following question: "Please describe, using as many chemistry terms as you know, what you just observed." The interviewee was given the opportunity to respond to this question (the first question after the demonstration was shown), and then asked to write a symbolic representation of a balanced chemical equation that represented the reaction. In the final question, the student was asked to draw a microscopic representation of the molecules that took part in the chemical reaction that they just wrote the balanced chemical equation to represent. All interviews were recorded and later transcribed, and the products of the interview (the balanced equations and drawings of the particles involved in the reactions) were photographed and evaluated later using the SMR and MMR. Below are two examples of student work, and explanations of the examples' SMR and MMR scores assigned.

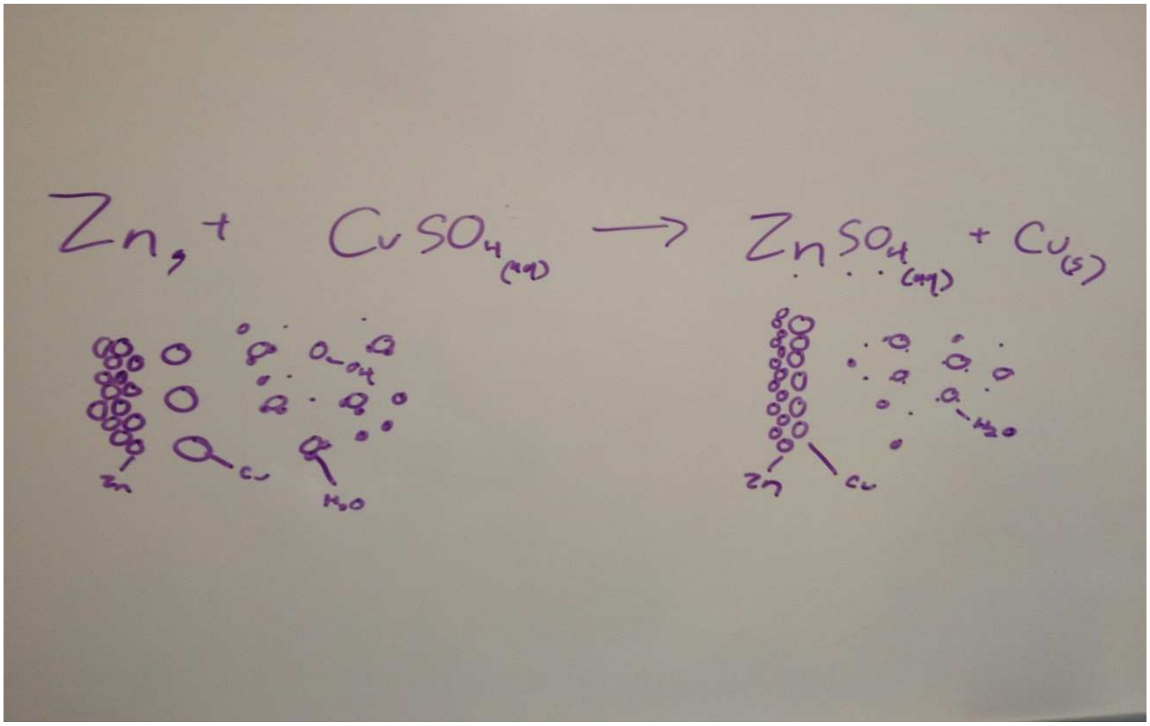

Figure 8. Student 2217 equation and drawing of redox reaction.

In Figure 8, the equation and drawing for the redox demonstration created by student 2217, the student correctly wrote and balanced a chemical equation that represented the reaction in the first demonstration. The student correctly noted the states of matter in the symbolic balanced equation as well. Using the SMR, this student scored a 3 for nomenclature, and a 3 for states of matter categories in symbolic mode, as well as a 3 for balancing the equation symbolically.

In the drawing directly below student 2217's symbolic representation, the student depicted zinc atoms in solid form, as a mass of individual atoms, and the mass is bar-shaped like the bar of zinc used in the actual demonstration. The student also depicted the copper (II) sulfate particles in aqueous solution, suspended in a water matrix. The water molecules are even shown to have their characteristic “bent” molecular geometry. The student’s drawing showed the copper atoms being attracted to the zinc bar, showing the copper atoms approaching the zinc metal in solution, as reactants, in the left side of the drawing (which depicted the reagents prior to reaction). In the product drawing to the right, the student depicted the copper plating on the outside of the zinc metal, as a result of the redox reaction. This student scored high in the states of matter category of the MMR for showing the atoms and ions in their correct state of matter (either as a solid, or as ions in an aqueous solution). However, this student scored mid-range in the MMR category of structure, since the polyatomic ions of sulfate are depicted only as singular circles, rather than as composed of 1 sulfur atom to 4 oxygen atoms per particle; but the water particles are shown to exhibit their characteristic bent molecular geometry. No attempt was made by this student to depict a balanced equation in the particle drawing of the reaction, so student 2217 scored low on the balancing portion of the MMR.

In the sample from student 22414 (Figure 9), this drawing earned high scores in the SMR in all three categories, since the metathesis demonstration was depicted in symbolic form correctly for all nomenclature of reactants and products, and the student correctly identified the states of matter in both reactants and products. This state of matter designation for the products is especially important, because by identifying the lead (II) iodide as a precipitate, the student has also identified the driving force for this chemical reaction, as well as identified the precipitate formed when the reaction was observed to produce a solid as a result.

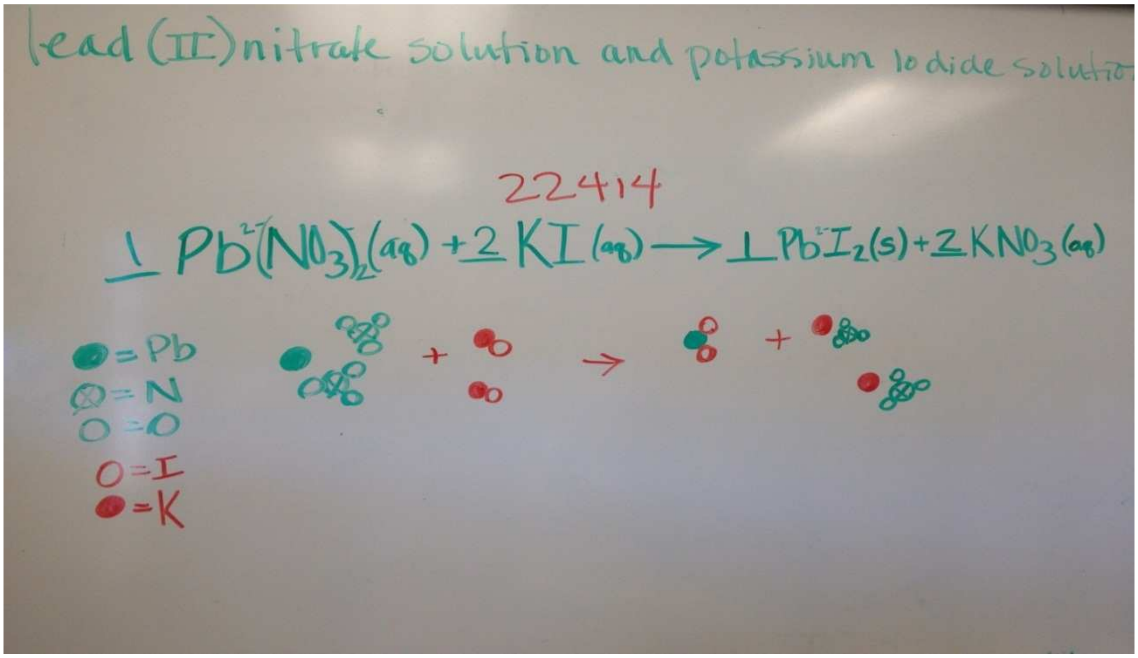

Figure 9. Student 22414 equation and drawing of metathesis reaction.

This student also scored high on the structure and balancing part of the MMR, for showing the correct ratios among the different particles involved as either reactants or products. However, this student scored midrange on the states of matter category of the MMR, since the lead nitrate and potassium nitrate are depicted as ions in solution correctly, and the lead iodide precipitate is depicted as a solid by the “touching” of the particles, but the potassium iodide reactant is also depicted as a solid, with the particles “touching” each other, and is not consistent with the fact that the potassium iodide was an aqueous solution, so the particles should be suspended in the solution like the other aqueous solutions depicted by student 22414 in the rest of the reaction.

Finally, some of the student drawings even showed movement of particles in solution, providing a deeper insight into the minds of the student when considering what is happening during a chemical reaction, which had not been considered prior to research. Figure 10 is an example.

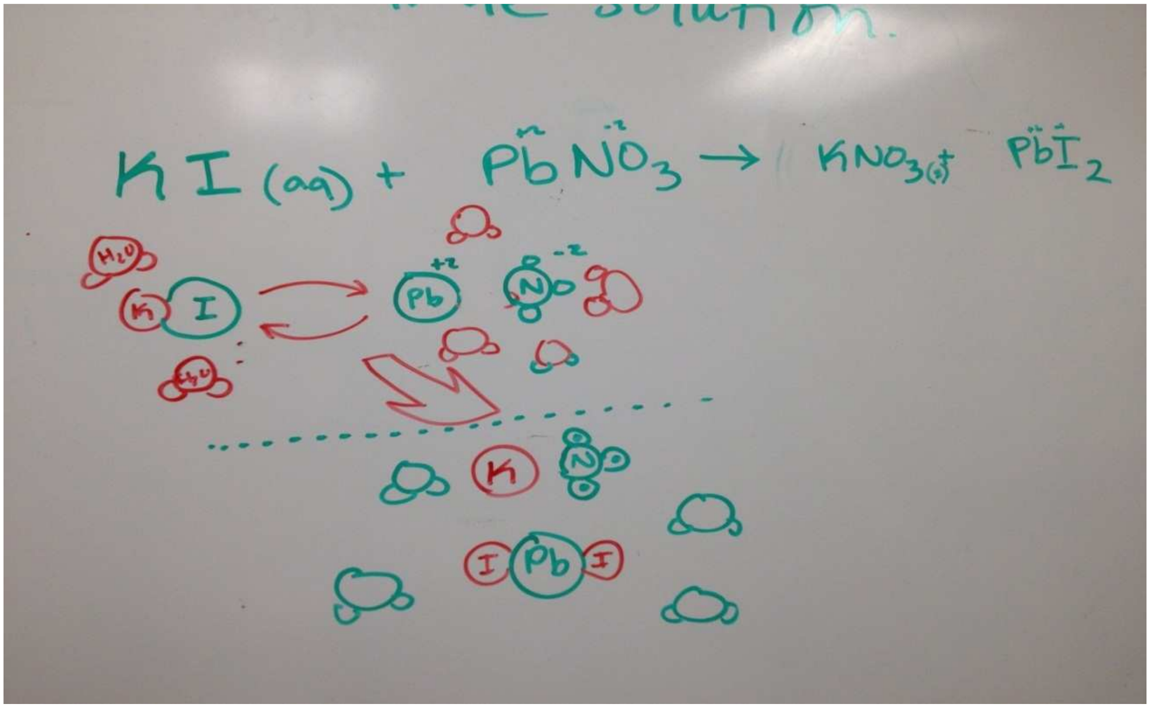

Figure 10. Student 22120 equation and drawing of metathesis reaction.

This student showed the ions exchanging places in solution using smaller arrows to indicate the intermediate change as it was occurring in solution. A larger arrow was used to indicate the transformation of reactant particles to product particles (designated by the horizontal dotted line in the drawing). The product particles are shown as either ions in an aqueous solution (indicating their continued solubility) or as particles that are "touching" each other in solution, the solid product and driving force in the symbolic equation. This student scored high in all categories of both the SMR and MMR except balancing, since the original symbolic equation is not balanced , and the subsequent drawing of the particles in solution are also not balanced. The results of all evaluation of student products using the SMR and MMR are summarized in Table 13.

Table 13

SMR and MMR Scores for Student Interviewees

Student # /Instructor /Gender	SMR Nomen.	SMR States	SMR Balanced	MMR Structure	MMR States	MMR Balanced	Pre/post ABCC score
11117/A/M	3	4	6	4	2	4	10/15
11113/A/M	4	5	4	6	2	6	15/16
11114/A/M	4	2	6	4	2	4	28/24
11137/A/M	6	6	6	5	4	5	24/25
22420/C/M	3	3	4	3	2	6	21/25
2217/C/M	3	4	4	4	6	4	23/25
22117/C/M	5	5	6	4	3	4	20/17
22116/C/M	6	6	6	4	2	6	18/20
22412/C/M	6	6	4	6	2	4	10/16
2244/C/F	4	4	6	2	3	2	27/27
22414/C/F	6	6	6	6	3	6	13/18
22120/C/F	6	4	6	3	6	3	12/9

Note: Scores on SMR/MMR are out of a possible 6 points, since both demonstrations' scores were combined by category.

The SMR and MMR values depicted in Table 13 were used in a 2 X 2 ANOVA, with the different classes/instructors as the independent variable and 2 levels: Instructor A and Instructor C (since Instructor B did not have any interview participants); and the different categories of SMR/MMR scores as dependent variable with two levels: symbolic (SMR score) and microscopic (MMR score). Results of the ANOVA indicated no significant difference between the classes in their SMR scores: F(1, 10) = .241, p = .634. Results also indicated no significant difference between the classes in their MMR scores: F(1, 10) = .030, p = .866. The mean and standard deviation for this data are summarized in Table 14.

Table 14

Mean and Standard Deviation for SMR and MMR by Instructor

SMR/MMR item	Instructor	M	SD
SMR Nomenclature	A	4.25	.63
	C	4.88	.48
SMR States of matter	A	4.25	.85
	C	4.75	.41
SMR Balanced	A	5.50	.50
	C	5.25	.37
MMR Structure	A	4.75	.48
	C	4.00	.50
MMR States of matter	A	2.50	.50
	C	3.38	.60
MMR Balanced	A	4.75	.48
	C	4.38	.53

A graph of the average scores on the different categories of the SMR and MMR by instructor are depicted in Figure 11 for visual comparison. The values used for this graph are contained in Table 14.

A series of Pierson product correlation coefficients were done on the scores between SMR, MMR, and ABCC to determine if low or high scores on one of these assessments might correlate to low or high scores on another. A large or small correlation coefficient is dependent upon the discipline within which the research question is being asked. For the behavioral sciences, correlation coefficients of .10, .30 and .50, irrespective of sign, are, by convention, interpreted as small, medium, and large coefficients, respectively (Green, 2010). The following is a summary of the correlations and the strength of their relationship.

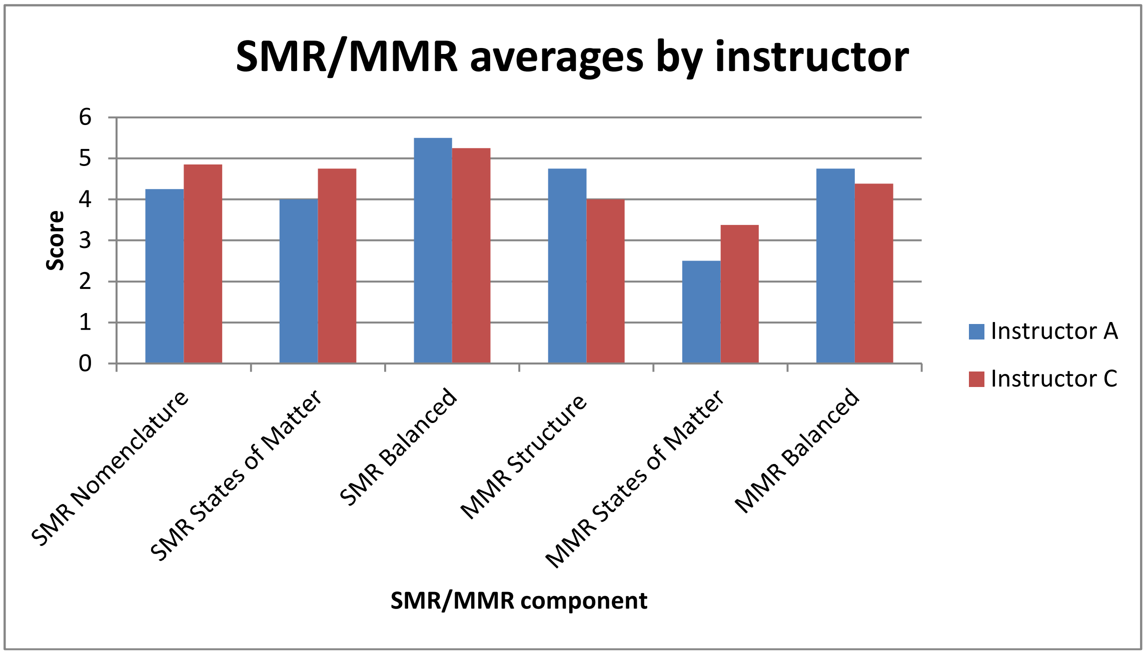

Figure 11. Average SMR/MMR component score by instructor.

The correlations between the total SMR of all students, total MMR of all students, and post-test ABCC scores for all students showed no correlations. So, the data were further subdivided by instructor: SMR, MMR, and ABCC scores were segregated by instructor and more correlations were performed, with no significant results. Again, the data were subdivided into the individual components of the SMR and MMR to compare these individual components to the ABCC. The individual components were based on the three categories each of the SMR and MMR – namely SMR nomenclature, SMR states of matter, SMR balancing; also MMR structure, MMR states of matter, and MMR balancing. Here, there were some correlations of interest. For all student scores (i.e., from both instructors) the correlation between SMR states of matter and SMR nomenclature was significant, $r(10) = .71$, $p < .01$. The correlation between MMR nomenclature and SMR structure was significant, $r(10) = .61$, $p < .05$.

Again, the data were subdivided into SMR and MMR categories by instructor and correlations were compared. For Instructor A, there was one significant correlation, which was the correlation between MMR balancing and MMR nomenclature, $r(2) = 1.00$, $p < .01$. For Instructor C, there were three significant correlations, the first between SMR states of matter and SMR nomenclature, $r(6) = .79$, $p < .05$; the second between MMR nomenclature and SMR states of matter, $r(6) = .78$, $p < .05$; the third was between SMR nomenclature and ABCC, $r(6) = -.79$, $p < .05$.

Most of the data reported and evaluated up to this point has been quantitative in nature. The more qualitative data resulted from the descriptions that students offered as a result of the interviews, when asked to describe, using as many chemistry terms as they knew, what happened during a chemical reaction they observed during a demonstration. Those results will be reported in the following section.

Verbal/Macroscopic Mode Evaluation

After transcription of the responses offered by the students, a word count showed common words used by all students to describe the reaction they had observed. In describing the reaction, words that were evidentiary in nature (based on the visual/sensory changes) were classified and counted, as were words and statements that were inferential. Table 15 gives the results of the word counts for each demonstration, by reaction type, for the correct inferences.

Once individual statements from the interviews had been categorized and counted, then a count of the total number of correct contingency statements for each student could be done. Table 16 is a comparison of the quantity of correct responses by each student interviewee, as well as the overall expertise score that was assigned to their response. When the student was asked: “Please describe, using as many chemistry terms that you know, what just occurred,” after being shown one of the two demonstrations, the student responses were categorized according to the contingency statements they reflected (Table 15). Correct contingency statements for each student were counted, and that student was then classified according to one of three designations: novice, practicing and expert (Table 16). To be classified as an expert, the student had to correctly state at least three contingency statements involving each reaction. As a novice, there had to be at least one of the two demonstrations shown for which the student did not have any (zero) correct contingency statements.

The category of verbal response (V/MM) was compared to the SMR and MMR results as well as ABCC score, and no correlations of significance were revealed. Table 17 summarizes all data collected and evaluated on the 12 student interviewees (a cross-referenced summary of Tables 13 and 16 together). If all information on interviewees was consolidated, the data in Table 17 could be compared. There was no correlation of level of V/MM to SMR or MMR or ABCC score.

Table 15

Inferential Statements Tied to Visual Evidentiary Statements

Count	Reaction	Evidence	Inference
2	Redox	A precipitate formed	Copper ions changed to solid copper
6	Redox	Copper-colored precipitate	Zinc is more active than copper
4	Redox	The color changed	Zinc solid (0 charge) changed to Zn 2+ ion Copper 2+ ion changed to copper solid (0 charge)
2	Redox	The precipitate is forming on the metal	This is a single replacement (redox) reaction
1	Redox	Blue liquid is not as blue after reaction	Copper ions were taken out of solution
1	Redox	The precipitate is red	Copper was the precipitate that formed on the zinc metal
3	Redox	A precipitate formed	This is a single replacement reaction
2	Redox	The zinc is dissolving	This is a single replacement reaction
1	Redox	A Cu precipitate is forming	What is left is a zinc sulfate solution
4	Metathesis	A precipitate was formed	This is a double replacement reaction
3	Metathesis	A precipitate was formed	The product was insoluble according to the solubility rules
1	Metathesis	A precipitate was formed	The product does not contain nitrate ion (NO$_3^{2-)}$ because nitrate is always soluble
1	Metathesis	A precipitate was formed	The ions switched places in the double replacement reaction
1	Metathesis	A precipitate was formed	The identity of the precipitate is lead iodide because that is the insoluble product

Table 16

V/MM Scores by Student Interviewee

Student # /Instructor /Gender	Redox correct contingency statements	Metathesis correct contingency statements	Total correct contingency statements	Expert, Practicing, or Novice
11117/A/M	3	4	7	Expert
11113/A/M	0	0	0	Novice
11114/A/M	1	2	3	Practicing
11137/A/M	0	1	1	Novice
22420/C/M	3	2	5	Practicing
2217/C/M	2	1	3	Practicing
22117/C/M	5	1	6	Practicing
22116/C/M	3	3	6	Expert
22412/C/M	4	1	5	Practicing
2244/C/F	3	3	6	Expert
22414/C/F	3	0	3	Novice
22120/C/F	3	2	5	Practicing

Table 17

SMR/MMR, V/MM and ABCC Scores of Student Interviewees

Student # /Instructor /Gender	Total SMR score	Total MMR score	Level of V/MM	Change in ABCC score/Final ABCC score
11117/A/M	13	10	Expert	+5/15
11113/A/M	13	14	Novice	+1/16
11114/A/M	12	10	Practicing	-4/24
11137/A/M	18	14	Novice	+1/25
22420/C/M	10	11	Practicing	+4/25
2217/C/M	11	14	Practicing	+2/25
22117/C/M	16	11	Practicing	-3/17
22116/C/M	18	12	Expert	+2/20
22412/C/M	16	12	Practicing	+6/16
2244/C/F	14	7	Expert	0/27
22414/C/F	18	15	Novice	+5/18
22120/C/F	16	12	Practicing	-3/9

Chapter 5

Discussion

This research was conducted to determine the impact that teaching practices, specifically instructional use of mode of representation, have on students' ability to learn chemistry. Results will be discussed first for the observations done in the classroom, then the assessments of student learning will be compared. Original research questions will be responded to in the context of this discussion.

Classroom Observations

The first set of quantitative questions posed in this research set the stage involving instructional mode of representation and student achievement in community college chemistry. By observing and recording the mode of instruction used by three instructors, from three different locations, over the course of an entire semester (an hour per week in lecture and an hour per week in the laboratory) this research provided a representative sampling of mode of representation used during instruction for both the lecture as well as the laboratory portions of the course.

Based on the classroom observations of these three chemistry instructors, the first question could be answered: What percent of the total instructional time in community college chemistry lecture and laboratory is spent using symbolic, macroscopic, or microscopic modes of representation? Figure 2 (page 85) in Results showed that when comparing overall percentage of time in the three modes of representation, all three instructors spent the majority of their instructional time in symbolic mode when lecturing. The focus on symbolic representation is supported by past research (Harrison

& Treagust, 2000; Kruse & Roehrig, 2005), which shows that the majority of instructional time in the university general chemistry classroom is spent in symbolic mode. This research confirms prior work at the university and shows that community college instructors spend the largest percentage of their instructional time in symbolic mode of representation during lecture.

Instructor A and Instructor B were almost exactly the same in their percent of time spent in symbolic mode during lecture, at 67% and 66%, respectively, while Instructor C spent a lot more time in symbolic mode: 75% (Table 5). Because of the focus on symbolic mode by Instructor C, microscopic mode and macroscopic mode were least used by this teacher, with 13% of Instructor C's time spent in microscopic, and 12% in macroscopic. Instructor C did not do any demonstrations, where the other two instructors utilized in-class demonstrations using chemicals or other physical materials to illustrate topics being discussed, which gave these two teachers a higher percentage of time in macroscopic mode. Although Instructor A did a few demonstrations in class and Instructor C did none, they both utilized the macroscopic mode 12% of the time. Instructor B performed frequent demonstrations, utilizing macroscopic mode 17% of the time, the highest among the three instructors. Several studies have shown that students experience difficulty understanding the microscopic and symbolic modes of representation (Ben-Zvi, Eylon, & Silberstein, 1986; Griffiths & Preston, 1992; Kozma & Russell, 1997) because these two modes of representation cannot be experienced. Students' thinking is influenced by their prior knowledge (Ausubel, 1968) and that prior knowledge is gathered via sensory information. When Instructor B used demonstrations in class, the students were fascinated and seemed to pay special attention to the explanations provided by the teacher that coordinated the microscopic and symbolic modes to the macroscopic that they had just witnessed in the classroom. Although Instructor B used more demonstrations in class than either of the other two instructors, this additional connection between the microscopic and symbolic to the macroscopic did not help the students on the ABCC post-assessment, since the mean for Instructor B's students was the lowest of the three populations.

When teaching the laboratory, Instructor A used almost exclusively an inquiry and/or problem-based approach but covered fewer topics; Instructor B used approximately half expository and half inquiry labs; and Instructor C used almost exclusively the expository laboratory format, but also covered more topics. This difference in orientation was in large part responsible for differences in mode of instruction among the teachers. If the percentage of time in instructional mode during teaching time is evaluated (Figure 3, page 86), two of the three instructors, A and C, spent the majority of their instructional time in the macroscopic mode of instruction, while the third, Instructor B, spent the majority of the time in symbolic mode.

Looking deeper into the instructional differences and comparing how much of each observational hour was spent by the teacher involved in direct instruction (up in front of the class teaching students as a group), Instructor C spent the most time overall instructing in the laboratory, with an average of 25% of each observational hour devoted to direct instruction. Conversely, Instructors A and B spent considerably less time at direct instruction (12% and 15%, respectively) and more time facilitating student work by walking around and assisting or providing resources and advice on individual student experiments during the lab. The difference in instructional mode and time spent on direct instruction in the laboratory had more to do with the type of laboratory experience that the students were involved in (inquiry and problem-based compared to expository) than anything else. Since Instructor A did all inquiry laboratories, less time was spent on direct instruction and more time was spent assisting individual student teams at the completion of their task. Instructor C used all expository laboratory activities, and covered more topics, so more direct instruction involving the usage of materials and equipment was necessary. Instructor C used macroscopic mode 64% of the time in laboratory instruction, the highest among all instructors; the low was Instructor B, who used macroscopic mode only 35% of the time (Figure 3). The macroscopic mode of representation was used to demonstrate usage of reagents, equipment and instrumentation necessary, and since Instructor A covered more curricular topics in labs, more labs were done, and more equipment and instrumentation was necessary.

The microscopic mode was almost entirely absent from Instructor A's mode of representation in the laboratory, with less than 1% of the time spent using molecular level comparisons of chemical interactions, although Instructor A was also the one who used the microscopic mode the most in lecture. Although this seems like a comparable imbalance in presentation, the difference was due to the fact that the inquiry and problem-based laboratory curriculum format that Instructor A used exclusively was focused on solving a problem and having students working in teams collaboratively. Instructors B and C utilized the microscopic mode considerably more than Instructor A, 8% and 9%, respectively, because these two instructors used more of the expository type of laboratory format. Instructor B used only about half inquiry, the rest were expository, and Instructor C used expository exclusively in the lab. Since Instructors B and C used more expository laboratory activities in comparison to Instructor A, the time spent using direct instruction with students was considerably less in Instructor A's laboratory, and more time was spent assisting the individual student teams in accomplishing the task at hand.

The chi square analysis of time (in minutes) spent in mode of representation over the entire semester was done to respond to the question: How do community college chemistry instructors differ from each other in their overall usage of the three different modes of representation? The chi square analysis of both lecture and laboratory showed a significant difference among instructors in their usage of mode of representation.

Although chi square analysis can determine that there is a significant difference, finding out where those differences are requires more specific information. The individual cells in the chi square analysis contained in Table 7 show the conditions that contributed to high chi square value were from Instructor A in microscopic mode, who was the instructor that used microscopic mode the most. Additionally, Instructor B contributed to the high chi sqare value for macroscopic mode, due to the numerous chemical demonstrations done as part of the lecture. Finally, Instructor C had high cell values for all three cells, since this instructor varied the most in comparison to the other two. Instructor C used symbolic mode the most, at the expense of the other two modes of representation. Instructor C used a very mathematical approach to the teaching of chemistry, and often made comments about how chemistry was just applied mathematics during the lecture portion of the course.

The chi square analysis for instructional use of modes in the laboratory portion of the course showed a significant difference among the instructors. Instructor C contributed a large cell value due to the almost complete absence of microscopic mode of representation during laboratory instruction. Only 1% of Instructor A's teaching time was in microscopic mode in the laboratory, and part of the reason for this is that Instructor A did not use a lab for molecular geometry, whereas both Instructors B and C used a lab that involved molecular models (stick-and-ball versions) to provide information on the topic of VSEPR (Valence Shell Electron Pair Repulsion Theory). The way both Instructor B and C taught the topic of molecular geometry involved considerable direct instruction, which gave them more overall minutes of direct instruction in the laboratory. There was also a greater overall amount of time spent by Instructors B and C using microscopic mode of representation to discuss and teach the topic of how molecules are shaped during the molecular geometry laboratory activity. A single laboratory session involving molecular geometry was enough to boost the amount of time spent in microscopic mode of representation for both Instructors B and C. This lab also increased the overall amount of time spent in direct instruction for both Instructors B and C, since the topic of molecular geometry involved considerable time demonstrating using molecular models with accompanying discussion. Instructor A only discussed the topic of molecular geometry in lecture. Since there was much less direction instruction in the inquiry/problem-based orientation that Instructor A used in laboratory, fewer minutes spent teaching by Instructor A in comparison to the other two instructors.

Instructor B had high chi square values in both symbolic and macroscopic modes of representation during laboratory instruction. These high cell values were because Instructor B spent considerable time demonstrating how equipment and instrumentation were used at the outset of each laboratory period, but also spent time discussing the chemical reactions taking place during the experiments, using symbolic means. Because of this focus on both symbolic and macroscopic modes of representation in the laboratory in comparison to the other two instructors, the cell values for Instructor B in macroscopic and symbolic were high.

Using chi squared analysis AND classroom observations, it became apparent that there was a variation in classroom instructional type and it was most clearly observed during the laboratory instructional time, in which the differences between direct instruction and inquiry lab processes resulted in marked differences in approaches to the focus on modes of representation.

Once differences among instructors were clear, differences with a single instructor between lecture and laboratory delivery could be compared. Among the instructors, the lecture was a more homogeneous delivery in which the instructors were influenced only by their own orientation towards instruction (Figure 2 in Results). In the laboratory, the activities and approach to the practical part of the course was more dependent upon type of laboratory activity used, whether it was inquiry, problem-solving, or expository. Although mode of representation varied significantly between lecture and laboratory for an individual instructor, the instructional use of mode in the laboratory was more heavily influenced by the type of laboratory activity the instructor used (Figure 3 in Results).

In order to respond to the final question about instructional mode: “Does the percentage of time spent in the different modes of representation vary according to curricular topic?” an ANOVA analysis was done on the mode of instruction over time. According to the ANOVA analysis, there was no difference among the instructors when the mode of instruction over time was considered and compared among them. The instructors did not vary significantly in instructional mode when compared over the entire semester.

As mentioned previously, chi square analysis determined there was a significant difference in the use of mode of representation among instructors. This apparent disagreement between results of the different statistical analysis may have more to do with how each analysis was performed and how the data was evaluated. When chi square was calculated, the total minutes in each of the three modes of representation for each instructor were summed from all of the individual observations (n = 12) over the entire semester, by mode. Conversely, the ANOVA analysis compared the variance in percent usage of mode on each individual observation date among the instructors over time. With the ANOVA, the number of observations, (n = 12) may have been too small for the analysis to be considered meaningful, since it is easier to violate the assumptions of ANOVA with small sample sizes.

To compare instructional usage of mode over time in the lecture venue for each instructor graphically, mode used by date was plotted and compared. The results showed trends in the usage of mode, by instructor. Figures 4-6 in Results show trend lines, with blue representing symbolic mode usage, red representing microscopic mode usage, and green showing macroscopic mode use. Comparing the trend lines displayed in these three graphs, some of the modes appear to change according to an inversely proportional relationship. Often, as symbolic mode decreases, microscopic mode increases; and vice versa, for all three instructors. Another interesting trend apparent in these graphs is that the symbolic mode decreases for all three instructors towards the end of the course, as microscopic mode increases. All three instructors get to a point towards the end of the semester when these two lines either cross each other (inverting the percentage of time spent in each mode) or come close to each other (showing an equal proportion of time in the two modes of representation). Additionally, the macroscopic mode (green lines) increases for all three instructors just after the midterm portion of the course.

In comparing the above referenced trends in mode of representation used by the three instructors over time, the topic covered during lectures was coordinated and compared to date, to see if the trends might coordinate to any common curricular topics covered in the course competencies. At the outset of General Chemistry I, the topic of nomenclature is taught during the first couple weeks of classes, a trend common to all three of the instructors in this course. This topic of nomenclature involves a lot of symbolism, because the students have to learn how the convention of the IUPAC (International Union of Pure and Applied Chemistry) dictates the usage of symbols for elements and compounds involved in communicating a chemical reaction. All three instructors spent a lot of time in symbolic mode of representation at the outset of the course, because all three instructors had to teach the topic of nomenclature. The highest percentage of symbolic mode usage came for all three instructors within the first three weeks of class; a common trend that shows symbolic mode has to be used in order to teach the topic of nomenclature.

Towards the end of the course/semester, Figures 4-6 show that all instructors followed a trend of decreasing their usage of symbolic mode of representation, and increasing the microscopic mode during instruction. Upon closer examination of the topic covered during this portion of the course for all instructors, the common topic was quantum mechanics – how the electronic structure of atoms influences their interactions on an atomic and molecular level. This topic necessitated instruction in microscopic mode, because the electron energy levels, shells, spins, and changes in this electronic structure were the topic of discussion. Common to all instructors was a decrease in the usage of symbolic mode, and an increase in microscopic mode; the trends in this change over time made all the instructors more similar in their proportion of time spent in mode.

Finally, each instructor exhibited a small increase in the macroscopic mode of representation just after the midterm portion of the course. The curricular topic associated with this common increase was energy: energy changes caused by a substance changing temperature (specific heat capacity), or by reacting chemically (Hess's law), or by changing phases (states of matter). All these types of energy changes can be measured by one of the senses, so instruction on the topic of energy and energy change used more macroscopic mode of representation during teaching and learning activities in the classroom.

In summary of the above analysis on instructional use of mode, although the three instructors varied significantly in their overall instructional use of mode (chi square analysis), they did not vary significantly when their instructional use of mode was compared among them by date (ANOVA analysis). This difference in statistical analysis can be interpreted that in any given day, there was not enough evidence to demonstrate a difference in the mode of instruction among instructors, but that through the course of the entire semester, there were differences among the teachers. The mode of representation used by each teacher was clearly influenced by the topic being discussed in the chemistry classroom, as evidenced by the ANOVA showing no difference in instructional use of mode over time. Nomenclature must be discussed using symbols, molecular geometry is demonstrated using ball-and-stick models that show how particles are put together, and calculations in chemistry are performed using balanced equations, stoichiometry, and conversions using ratios and proportions.

However, it is possible to include more modes of representation in the teaching of chemistry. When instructors are discussing nomenclature, instead of relying exclusively on the symbols used by chemists and dictated by the IUPAC, drawings that show the ratio of atoms in a compound should also be included, connecting the symbolic mode of representation to the microscopic mode. When doing calculations involving stoichiometry, in the traditional method of giving students a rote method for solution, teachers are reinforcing an algorithmic approach without use of the underlying chemical concepts involved in the reaction itself. Familiarity with the interconnectedness of the three representational systems, also referred to as integrated conceptual understandings by Krajcik (1991), is important for understanding chemistry concepts and phenomena. In order to be able to understand the reasoning about why chemical reactions and other chemical phenomena occur, students should be able to constantly navigate between the three modes of representation, using each mode at an appropriate stage of their reasoning (Sai, Treagust, & Chandrasegaran, 2012). This is an interesting comparison and dichotomy, especially now that the results of student achievement can be compared to instructional mode.

Assessment of Basic Chemistry Concepts, Pre- and Post-Assessment Results

The original version of the ABCC, then called the Chemistry Concepts Inventory (CCI) was developed by Mulford (2002) was administered to university freshmen at the outset of a first semester general chemistry course and showed an average score (n = 1418) of 45.5%. The average pre-test scores of the n = 78 students in this research was 46.2%. The average post-test score of Mulford's sample was 50.5%, the average post-test score for the students in this research was 52.9%. In this research, the sample of three instructors/classes were from the community college. Mulford's sample was taken from university classes, but both venues involved the same course: General Chemistry I lecture and laboratory. The student populations were comparable based on the course being taught, as well as their pre- and post-test comparisons.

An ANOVA was done on the three populations of pre-test scores, and showed no significant difference between the three different populations of students at the outset of the semester (Table 10 in Results). The pre-test scores of the student populations from the three instructors used in this research were not significantly different from each other, as measured by the ABCC, which meant that no adjustment in post-test ABCC scores was necessary.

Results of the student t-test for the 78 ABCC scores, using a matched subject design between pre- and post-test scores for each student by instructor, showed that only one of the three populations of students had significantly greater gains in ABCC score from pre- to post-assessment. Students from Instructor A's class had a mean post-test ABCC score that was significantly greater than the mean of their pre-test ABCC score. Although all three student sample populations from the three instructors made gains in their scores, only the gains made by Instructor A's students were significant (Table 12 in Results). Therefore, to answer the question: "Does the focus on mode of representation by the instructor influence student achievement, as measured by a change in ABCC score?" Significant achievement on the ABCC was accomplished by the student population of Instructor A, and Instructor A's usage of mode of representation was significantly different than the other two instructors.

Chemical understanding has been shown to be improved when this model representing the particulate nature of matter is used in instruction (Gabel, 1993; Pickering, 1990; Sanger, 2000). By incorporating descriptions of how and why the particles are interacting in a chemical reaction, Instructor A helped students to make the connection between the microscopic, macroscopic, and symbolic representations used by chemists when symbolic mode is used, and that is why the students in Instructor A's section of General Chemistry I were more adept at the conceptual based problems on the ABCC.

There were students in both Instructor B and Instructor C's sections who earned A grades in the course; however, a deep conceptual understanding of the nature of chemical processes is not always present in students who earn good grades in chemistry. According to Pickering (1990), algorithmic problem-solving ability is not necessarily an indication that students have a conceptual understanding of the particulate nature of matter. Pickering found no connection between using algorithms to solve chemistry problems and understanding the chemical concept underlying that problem. In a similar study at the university level, Nakhleh (1992) found that the conceptual problems solving capability of first year general chemistry students lagged far behind their algorithmic problem solving ability. She used paired exam questions, similar in composition to over half of the questions on the ABCC, to compare how well these university students solved calculation based problems in comparison to their understanding of the conceptual basis for the application of an algorithm. In Pickering's study, 31% of the students had low conceptual, but high algorithmic ability in terms of solving chemistry problems. In a follow-up study done by Nakhleh in 1992, also using university chemistry students, she tested a larger population to determine if they were high or low algorithmic problem solvers, and high or low conceptual problem solvers. By the end of the term, 85% of the students in the overall general population were good algorithmic problem solvers. The students from the larger overall population of students in the course were then grouped into one of four categories and interviewed. Of the six students who were interviewed, four had A grades in the class, and all six were declared chemistry majors. The interviews showed that students with high algorithmic problem solving ability use algorithms to solve conceptually based problems regardless of their conceptual problem-solving ability.

Similar results were obtained by Nurrenbern and Pickering (1987) in a series of studies involving university freshmen from three different locations around the United States. Gas law problems and their underlying conceptual framework were investigated in a series of questions from exams. In each study, the number of students who could solve traditional gas law or stoichiometry problems was much higher than the number of students who could answer conceptual questions about the reactions used to solve the problems mathematically. Too often in the teaching of chemistry, it may be easier to help the students do well on an exam by teaching methods of problem-solving, rather than assisting them in understanding the underlying conceptual framework for the interactions among particles. Instructor C used a very mathematical approach to teaching chemistry, and made many comments about the role of mathematical reasoning in the discipline. This teacher even stated a preference for being a math teacher, as math was more “straight forward” than chemistry, with fewer exceptions to the “rules.”

As a result of research done by Nakhleh (1992) and her colleagues, suggestions for teaching chemistry include more emphasis on the particulate and conceptual (aka microscopic mode of representation) approach. She stated, “Current methods of teaching chemistry are, perhaps, not teaching chemistry, but teaching how to get answers to selected algorithmic problems” (p. 191). The reliance students seem to have on algorithms to solve problems comes from the most proficient teachers; even those who show numerous ways to approach a problem are still using algorithms to solve these problems, and rarely address the underlying chemistry concepts (and particulate nature of matter). When chemistry teachers draw attention to and describe each mode conceptually, linking the modes in teaching and demonstrating transition among the modes, chemistry learners are assisted with the difficult formal thought concepts necessary for deep conceptual understanding of chemistry (Gilbert, 2005; Gilbert & Treagust, 2008; Hoffman & Lazlo, 1991, 2001). Familiarity with the interconnected nature of these representational systems, also referred to as integrated conceptual understandings (Krajcik, 1991), are important for a thorough understanding of chemistry.

All of the students in this study who took the post-ABCC assessment from all three of the instructors had retained in the course, and as a result of this retention, had multiple opportunities to take instructor-written assessments. Although many of these students may have experienced success during these assessments, they may not have understood the chemical principles behind their manipulation of the algorithms they used to solve the problems. It has been shown, through research mentioned above, that mathematical problem solving ability and conceptual understanding of chemistry are often skills developed in exclusion of one another, without students making the necessary connection between them.

Interviews of Students

When the interviews were announced, the end of the semester was within 2 weeks, and many students simply did not have the time to volunteer for interviews. Of the 12 who did, 4 were from Instructor A, and 8 were from Instructor C. Instructor C had the largest population of students who had also agreed to take the pre- and post-ABCC to recruit from for the interview stage of this research.

Correlation coefficients revealed a number of strong correlations between portions of the rubrics used to evaluate student understanding by mode of representation. Using the individual categories of the SMR, namely nomenclature, states of matter, and balancing, there was a correlation among all students (from both instructors) of nomenclature to states of matter within the SMR. The students who were best at figuring out the correct formulas for the compounds used in the demonstrations were also meticulous in their notation of the states of matter that these reagents were in: (s), (l), (g), or (aq) designation. These designations are especially important in the two types of reactions that were shown to the students, since recognizing that a solution is aqueous is a precursor to understanding that there are ions available in that solution for potential chemical reaction, whether that reaction is a redox or metathesis reaction.

Between the SMR and MMR, there were also correlations for all students as a whole (regardless of their instructor). The correlation between SMR nomenclature and MMR structure was significant. This correlation shows that the students in both of the classes understood the bridge between the symbolic formulas whose nomenclature is dictated by rules of the IUPAC, to the actual ratios of the component atoms in the compounds in the nomenclature. It is important in chemistry to understand that when the symbols $Pb(NO_3)_2$ are used, the nomenclature references the ratio of atoms in the compound as 1 lead, 2 nitrogen, and 6 oxygen atoms per unit. The student drawings of the structure of the particles were correlated highly to their representations of the IUPAC nomenclature for those particles.

In comparing student scores on the SMR and MMR components by instructor, there were numerous correlations that would be considered significant. For the students in the class taught by Instructor A, there was a single significant correlation between MMR balancing and MMR nomenclature, a perfect linear correlation of 1. Although the evaluation of the category of nomenclature was independent of the category of balancing, the students in Instructor A's class understood the microscopic implication of the structure of particles and applied the law of conservation of mass perfectly to that understanding of structure. Instructor A used the highest percentage of the microscopic mode of representation when teaching. The students from Instructor A's class who were interviewed had the highest scores on two of the three measures of microscopic understanding, as measured by the MMR's structure and balancing categories. This shows that the students, who did well at the structure portion of the MMR, putting together the atoms that make up the individual particles taking part in the chemical reaction, also did well at balancing those particles between reactants and products. This interview process and results are comparable to those of Yarroch (1985), who interviewed high school chemistry students on how they balanced simple reactions, and then asked them to diagram a microscopic version of the system in the balanced equation. All of the students could successfully balance the equation given (using algebraic manipulation of the equation), but over half of them could not draw a correct molecular diagram to explain the equations. Delving deeper into the results of the students who could not draw appropriate particle level diagrams, those who were unsuccessful could determine the correct number of particles on each side of the equation, but could not differentiate between the coefficients and subscripts in the balanced equation to translate the information into correct molecular level ratios of the particles involved in the reaction for the reactants and products. An example of this inability to translate the coefficients and subscripts in the balanced equation is the reference of $3H_2$ as six circles touching each other (incorrect), instead of three sets of two circles each (correct) as representing three molecules of hydrogen gas in the balanced equation given by: $N_2 + 3H_2 \rightarrow 2NH_3$.

For the students in Instructor A's class to have a perfect linear correlation between MMR nomenclature and MMR balancing shows that the students in Instructor A's class were better able to connect nomenclature and the structure of particles than their peers in Instructor C's classes. Many of the students in both instructors' classes made the kinds of errors described by Yarroch (1985) during the interview process. The most common error was in depicting a polyatomic ion as a single, undifferentiated circle, instead of a charged particle composed of a set ratio of atoms, which demonstrates confusion about the meaning of the subscripts in the chemical formula.

Ben-Zvi et al. (1987) agreed with Yarroch's (1985) analysis, and used a different equation in their research – that for the combustion of hydrogen gas: $2H_2 + O_2 \rightarrow 2H_2O$. They discovered that an appropriate interpretation for this equation requires the learner to know many conceptual ideas about the reaction taking place: the structure and physical state of the reactants and products, the quantitative relationships among the particles (both measured in this research by the SMR and MMR), and the dynamic nature of the particle interactions. Being able to translate between the algorithmic manipulation of coefficients during the process of balancing an equation and the microscopic structure and properties of each reactant or product substance is a complex task. If a student has multiple ways of learning using visual, experiential, audible, tactile or other sensory learning, then that learning is connected to the conceptual framework that translates between microscopic and symbolic modes of representation, and they are more likely to understand what the symbols in a balanced chemical equation mean about the reaction at the microscopic level, rather than simply relying on rote algebraic manipulation to solve problems.

Students in Instructor C's classes had two correlations of interest that were significant: the first between SMR states of matter and SMR nomenclature. Those who did well in the nomenclature portion of the SMR also did well at labeling the states of matter in which these reagents were found. Instructor C was also the teacher who used the symbolic mode the most in teaching (Figure 2). The results of SMR in Figure 4 and Table 12 in Results show instructor C's students did the best at their symbolic representations of chemical reaction, in comparison to Instructor A's students.

There was also one negative correlation, that between the SMR nomenclature and ABCC scores. If the students in Instructor C's classes did not do well in the symbolic representation of nomenclature during their interview, they also did not do well on the ABCC score. Conversely, Instructor C's students did not do as well on their microscopic (MMR) scores as Instructor A's students, and made errors when interpreting the coefficients and subscripts in their balanced equations. Instructor A's students were able to correctly write a balanced equation (high SMR scores), but were more likely to misinterpret the coefficients and subscripts in their microscopic drawings – leading to a lower MMR score.

Results from this research are supported by a similar study by Sanger (2005), who used his own university introductory chemistry students and evaluated their understanding of conceptual versus algorithmic reasoning using test items in stoichiometry. In this part of his research, Sanger administered a written test that used paired questions to assess students' stoichiometric problems solving ability independent of their conceptual understanding of what was happening during the particle level interactions of the chemical reaction. He asked his students to write a balanced equation that represented a given particle picture, and then to perform two stoichiometric calculations using their balanced equation. The most common student errors in Sanger's research were the same as in this research, that the students were confused by the coefficients and subscripts and what they meant about the ratios of atoms in a compound versus the number of particles reacting or being produced. Additionally, in Sanger's study, fewer than half of the students who mixed up coefficients and subscripts were able to correctly perform the stoichiometric calculations necessary to solve the numerical/algorithmic part of the problem. Sanger's research showed that students could not interpret the symbolic given the microscopic, and as a result also cannot perform the mathematical given the microscopic. My research lends to the idea that students cannot translate to the microscopic after they have created the symbolic. Either way, the indicator of confusion seems to be the incorrect interpretation of coefficients and subscripts.

Some of the most interesting comments during the interviews came when the students were asked to draw a representation of the particles based on their balanced chemical reaction. One of the students in Instructor C's (who rarely used microscopic mode) class was perplexed at the request, and asked more clarifying questions. Finally, this student stated: "Well, this is not something we ever did or were asked to do in class, but I'll give it a try." Conversely, when the students in Instructor A's class (who used microscopic mode the most) were asked to represent the particles using drawings, they responded quicker and made fewer erasures. The students in instructor A's class also more often created a key to their drawings to show the identity of the individual atoms involved in making up the particles.

An additional aspect of chemical understanding arose during the interview process that was not anticipated, that of the static versus dynamic model of chemical interactions. Of all 12 students who were interviewed in this research, only one student had what Andersson (1986) would term a dynamic model for the interactions of the particles involved in the chemical equation. Student 22120 (Figure 10 in Results) drew arrows to represent the exchange of ions in solution during the double replacement/metathesis reaction and showed the ions as individual entities suspended in a matrix of water. The same student also showed that the products crossed a line, represented by a dotted line between reactant and product particles, when the transformation between the particles was complete.

Andersson (1986), in his studies of Swedish students, classified student responses to a question involving a similar redox reaction into one of five categories. The first was "it's just that way," in which the student is uninterested in the change, but notices it. The second involves displacement from one physical location to another, in other words, a coating just materializes from the air or the water onto a metal. The third is that the material is modified, not that a chemical reaction has taken place but more of a physical change that might be indicated by changing color due to a temperature change. The fourth is transmutation, where one substance changes into another entirely, as in iron becoming carbon. The fifth (and the only correct interpretation) is that a chemical interaction occurs. According to Andersson, all of the first four categories of student explanations display a lack of understanding that matter is composed of particles. The particles are in constant motion and react with each other by breaking and forming bonds between the particles. The students in this research were not confused about any of these issues. In fact, Student 22414 from Instructor C's class did especially well (Figure 10 in Results) in the interview, and had well-formed perspectives on the microscopic structure based on nomenclature and changes in structure during each of the demonstration shown during the interview.

Although this student did relatively well in the interviews when relaying the microscopic nature of the particles involved in a chemical reaction, the post-ABCC score was average in comparison to the other student interviewees. This same student expressed, "Yes, I understand the molecule part, but my grade is not as good as I wish it was, because I just don't get all the math." When this student was questioned further about where these ideas concerning the interaction of particles originated, the reply was that the student had a good high school chemistry teacher who was a “modeler,” referring to a teacher post-education program sponsored by Arizona State University that uses a particulate nature of matter as the focus of chemistry instruction. This particulate nature of matter orientation towards the teaching of chemistry also uses the ABCC as a measure of pre- and post-course knowledge among the practitioners of the genre of instruction referred to as modeling. Thus, it may have been that Student 22414 was a good conceptual problem solver, but not as proficient at algorithmic problem solving. In fact, more than one of the student interviewees’ cited their high school chemistry teacher as providing the basis for their conceptual understanding of basic chemistry ideas, rather than their college teacher. Student 11117, who was considered an expert in the description of the chemical processes going on during the demonstration said:

> College chemistry was just a review of what I already knew from high school. Even though my teacher did talk about the atoms and molecules much, I already knew that stuff. What I learned about in college was more of how to apply the math.

None of Andersson’s (1986) first four student classifications occurred in this research, but when student 22120 used smaller arrows to represent interim activities of ions in solution, and then a larger arrow to indicate a change of reactant particles into product particles, the dynamic nature of the chemical interactions and reaction were shown. Student 22120 had a very deep conceptual understanding of the chemical processes involved in metathesis reactions, and scored well in the categories of SMR involving nomenclature and SMR balanced for both metathesis and redox reactions, showing further understanding of structure and interactions between particles. However, this same student did not do well in the balancing or structure category in MMR for the redox demonstration, indicating that there may have been a clear understanding of the particle interactions in the metathesis demonstration, but a weaker conceptual understanding of the interactions that occur in redox reactions.

Metathesis reactions are simpler in concept that redox, since the charges (basic subatomic structure) of the particles involved in metathesis reactions do not change. The driving force (and visual macroscopic evidence) for the metathesis reaction that the students observed in this research was the formation of a precipitate, which uses solubility rules as a guideline. An insoluble product (the precipitate) is easily observed by a change in color, or a change in the transparency of the solution, when the solution becomes more opaque. This change usually happens instantaneously, and is macroscopically evident. Chandrasegaran's 2007 study of Singapore chemistry students used the same metathesis reaction used in this research (lead II nitrate and potassium iodide) in a pencil and paper assessment of post-intervention learning. In Chandrasegaran's study, 91% of the students were able to correctly pick out the ionic equation, but only 75% were able to correctly display understanding behind the molecular level reasoning for the lack of spectator ions in the final net ionic equation. This lack of understanding of the microscopic process of removing the precipitate ions from solution showed that 11% of the students might be able to correctly pick out the correct algorithmic manipulation of the symbolic equation, but they did not understand the microscopic rationale for the equation they chose as correct.

When the students in this research were shown the demonstration of the redox reaction, it took longer to occur, and was more difficult to detect visually when it did. Macroscopic evidence of the redox reaction was also different from the macroscopic evidence the metathesis reaction. In the redox reaction, a precipitate formed on the metal, providing an opportunity for a displacement or transformation error (Andersson, 1986) by the student. In a redox reaction, one metal is more active than another, and therefore is more likely to donate some electrons (become oxidized) than a metal ion in solution. When this donation of electrons takes place from the solid metal to the ion in solution, the macroscopic evidence of the transmission is a precipitate forming on the solid metal, the identity of that precipitate is the metal that was formerly an ion in solution that has now been reduced. This microscopic change in the structure of particles that make up the chemical reaction is more difficult to interpret because the visual (macroscopic) evidence is more difficult to detect and takes place over a longer period of time.

Similarly, Chandrasegaran's 2007 study used the exact same reaction, but in a written assessment of the Singapore chemistry students. Oly 40% of the students were successful in answering the redox item, in comparison to the 91% who correctly responded to the metathesis question. The incorrect rationale described by the students in Chandrasegaran's study was almost exactly the same as the incorrect rationale displayed by 3 of the 12 students interviewed in this study: that the solid formed on the metal in solution was due to insolubility of the precipitate instead of an exchange of electrons in solution, causing a metal ion in solution to become a solid metal. In essence, the students in both studies were confusing the driving force behind a metathesis reaction (microscopic) with the driving force of a redox reaction, based on the common (macroscopic) observation of the formation of a precipitate.

Four of the 12 students in this research made another mistake that some of Chandrasegaran's students made, and that was to assume a solid metal had the same oxidation state (charge) as a metal ion in solution. This further underscores the students' confusion of the conceptual basis for redox reactions, that a change in charge indicates electron transfer. All of the errors are on the microscopic level; students might be able to determine a net ionic equation for either metathesis or redox reactions, but unless they understand the conceptual basis for these reactions taking place, their knowledge is more superficial and algorithm based.

Finally, the verbal descriptions offered by the students were evaluated using an observational/inferential contingency statement set, to answer the last question: Is there a relationship between instructional use of modes and the student's ability to use evidence as explanation of an observed phenomenon? The student responses to the question: "Please describe, using as many chemistry terms as you can, what you just observed" varied and were differentiated from each other in many ways. By coordinating the contingency statements that each student made that would be considered correct, the level of student expertise in verbal description was assigned (Table 16) and could be compared to their SMR and MMR scores (Table 17). These correlations proved to be as difficult to make (none of the correlations yielded any results of significance) as they were to classify.

From the analysis of all classroom observations, student assessments, direct observation and interviewing of students from the different classes, I have come to the following conclusion. My research suggests that there are multiple factors that help students obtain a significant change in their knowledge of basic chemical concepts. The first factor is instructional mode of representation. Past research, mine included, suggests that more microscopic mode of representation, used with appropriate comparisons and transitions between modes, can help students in their conceptual knowledge and understanding of basic chemistry concepts. The second factor shown to assist students in a deeper conceptual understanding of chemistry concepts is inquiry and/or problem-based laboratory format. When students work in groups and have the opportunity to solve problems, applying the knowledge gained in the lecture classroom to macroscopic observations they make in the laboratory, their conceptual knowledge of the microscopic particle interactions will benefit. Additionally, a strong high school experience, rich in particle nature models for matter, is certainly influential to the conceptual understanding of the community college student, and the pre-requisite of high school chemistry or introductory chemistry is absolutely crucial for the initial development of a basic understanding of chemical concepts for the general chemistry student, whether they continue their education at the community college or the university.

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APPENDIX A

STUDENT RESEARCH PERMISSION LETTER

Dear Student Participant,

I am a residential chemistry faculty at Chandler-Gilbert community college and PhD candidate at Arizona State University; and I am conducting research in cooperation with my faculty advisor: Dr. Dale Baker of Arizona State University. We are interested in how students use different modes of representation in learning and communicating in chemistry, and we would like to invite you to participate.

Your participation is voluntary, and will involve a pre- and post- assessment using an instrument called the ABCC (Assessment of Basic Chemistry Concepts). The ABCC is a non-mathematical evaluation of chemistry concepts, and is informative as to particular common misconceptions that research shows many first year chemistry students experience. The data from this assessment will be used to inform the teaching and learning of community college chemistry, and may be able to help students learn chemistry more efficiently in the future.

Your participation is completely voluntary, and you can choose to withdraw at any time for any reason, your grade in the course will not be affected. You must be 18 years or older in order to participate. Confidentiality will be maintained by assigning code names to responses. Data from this study may be used in reports, publications or presentations. Your name will not be used, and data will be presented only in aggregated form. If any individual responses are used in publication, any identifying information will be removed. There are no foreseeable risks or discomforts associated with your participation, other than those experienced in every day life.

If you have any questions concerning the research study, please contact the research team at: dale.baker@asu.edu or 480-965-6057 or Lorelei.Wood@cgcmail.maricopa.edu or 480-857-5546. If you have any questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk, you can contact Maricopa Community College Human Subjects Institutional Review Board at: irb_office@domail.maricopa.edu or 480-731-8701 and the Arizona State University Chair of the Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at 480-965-6788.

Print name here:______________________________________

Signature: ____

Date: ________________

Student code: __________________

APPENDIX B

STUDENT RESEARCH PERMISSION LETTER: INTERVIEW

Dear Student Interview Participant,

I am a residential chemistry faculty at Chandler-Gilbert community college and PhD candidate at Arizona State University, and I am conducting research in cooperation with my faculty advisor: Dr. Dale Baker of Arizona State University. We are interested in how students use different modes of representation in learning and communicating in chemistry, and we would like to invite you to participate.

This interview will take about one hour to complete, and will involve your reporting some background information about your personal educational history (in chemistry and mathematics). Then, you will watch two videos and discuss your interpretation of the events in the videos with the researcher. Your verbal responses will be recorded via audio tape, and any equations you write will be recorded in a digital photograph.

The interview is completely voluntary, and you can choose to withdraw at any time for any reason, and your grade in the course will not be affected. You must be 18 years or older in order to participate. At the close of the interview, each participant will be compensated at the rate of $10.00 for the interview. If you choose to leave before the interview is complete, your compensation will be prorated at the rate of $2.50 per 15-minute increment completed.

Confidentiality will be maintained by assigning code names to responses. Responses to these interviews will be used to inform the teaching of community college chemistry, and may be used in reports, publications or presentations. Your name will not be used, and data will be presented in aggregated form, and if any individual responses are used in publication, any identifying information will be kept confidential. There are no foreseeable risks or discomforts associated with your participation, other than those experienced in every day life.

If you have any questions concerning the research study, please contact the research team at: dale.baker@asu.edu or 480-965-6057 or Lorelei.Wood@cgcmail.maricopa.edu or 480-857-5546. If you have any questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk, you can contact Maricopa Community College Human Subjects Institutional Review Board at: irb_office@domail.maricopa.edu or 480-731-8701 and the Arizona State University Chair of the Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at 480-965-6788.