

ABSTRACT

MCBROOM, RACHEL ANN. Pre-Service Science Teachers' Mental Models Regarding Dissolution and Precipitation Reactions. (Under the direction of Dr. John C. Park.)

This study described pre-service secondary science teachers' mental models of dissolution and precipitation reactions. The study took place at a mid-sized master's granting public institution located in southeastern United States. The twelve participants were either juniors or seniors in the Bachelor of Science in Science Education program or first year students in the Master's of Arts in Teaching Science Education program. All had completed two semesters of general chemistry with final grades of C or better.

Participants were shown six videos – four showing ionic solids dissolving in water and two of precipitates forming from the combination of the previous four ionic solutions. After each video, participants completed a questionnaire consisting of multiple choice questions and tasks involving the writing of chemical equations and providing particulate level drawings of the observed chemical phenomenon. Each participant was interviewed individually to explain his/her answers and to allow the researcher to probe the individual's understanding of the dissolution process.

Although the study used a population not previously reported in the literature, results from this study matched previously reported findings for populations of high school students, college students, and pre-service elementary teachers. Participants demonstrated several common misconceptions related to the topics of dissolution and precipitation reactions. These misconceptions included dissolving is the same as melting, ionic solids react with the

solvent (water) to form new compounds, and precipitation reactions result in the production of two chemical compounds. The study also discussed the level of consistency exhibited by individuals in their multiple representations and explanations of the same chemical phenomenon.

Pre-Service Science Teachers' Mental Models Regarding Dissolution and Precipitation
Reactions

by
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DEDICATION

This dissertation is dedicated to my husband, Douglas, and my son, Andrew Carl. It is also dedicated to all of the pre-service science teachers with whom I have worked.

BIOGRAPHY

Rachel was born Rachel Ann Russ in Whiteville, North Carolina. She attended the University of North Carolina at Pembroke, where she double majored and earned her Bachelors of Science in Science Education and Chemistry in 1997. During her time as a student at UNC Pembroke, Rachel was advised and mentored by Dr. Peter Wish, who encouraged her to pursue a Ph.D. and her dream of becoming a college professor. Upon graduation, Rachel accepted a high school teaching position with Cumberland County Schools and immediately enrolled in the masters program at North Carolina State University. She earned her Masters of Education in Science Education in 2000. Shortly after graduation, Rachel married Douglas, a high school math teacher.

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In Fall 2003, Rachel was hired full-time to be the program coordinator for the undergraduate Science Education Program at UNC Pembroke. She enjoys assisting pre-service and practicing science teachers through grants, professional development, and mentoring. In 2010, Rachel and Doug moved into their new home and welcomed their son, Andrew Carl, into their family.

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CHAPTER 1
INTRODUCTION

Problem

What do chemical reactions, sub-cellular processes, and planetary motion all have in common? In addition to being topics taught in many science classrooms, these concepts cannot be observed directly by the unaided human eye. Most phenomena of interest to the scientific community and therefore science education exist beyond the perceptual abilities of human beings. These phenomena vary in size from sub-atomic particles to the heavenly bodies of the universe. Our understanding of these phenomena rests on our abilities to interact indirectly with the phenomena through the use of representations (Kozma, 2000). Based on experiences with these representations, learners construct their own mental models of these phenomena (Greca & Moreira, 2000). As educators and researchers we are interested in how learners' mental models align with the scientifically accepted conceptual models and strategies for influencing learners' mental models. Because pre-service teachers represent a unique transition between individual learners with individual mental models and members of the larger scientific community responsible for development of conceptual models, this study will look at the mental models held by pre-service science teachers regarding the topics of dissolution and precipitation reactions.

Theoretical Framework

Constructivism has been cited as a major influence on mathematics and science education in the past 20 years (Applefield, Huber, & Moallem, 2000; Jones & Brader-Araje, 2002; Mathews, 2000). Although constructivism has many variations, the most basic belief is that individuals learn by constructing their own knowledge as opposed to that knowledge being transmitted from one person to another. Though no one person is credited with the

origins of constructivism, Piaget, Bruner, Dewey, and Vygotsky are frequently linked with the theory (Applefield et al., 2000; Jones & Brader-Araje, 2002; Lowenthal & Muth, 2008; Mathews, 2000).

Cognitive science is an interdisciplinary science that draws upon many different fields, including psychology, artificial intelligence, and philosophy and is focused on the development of theories in the areas of human cognition, teaching, and learning. The contributions of cognitive science to understanding learning and teaching have been acknowledged by many researchers (Clement, 2000; Gobert & Buckley, 2000; Greca & Moreira, 2000; Hestenes, 2006; Matthews, 2007a). Cognitive science has been especially important in model-based teaching and learning theories.

Models have long been recognized for their importance in the sciences (Matthews, 2007a). In education, two specific types of models hold significant value— mental models and conceptual models. Mental models are described as internal representations of real phenomena created by individuals in their minds, while conceptual models are considered consensus models created by scientists, teachers, and/or researchers usually for the purpose of instruction (I. M. Greca & M. A. Moreira, 2000). Mental models align with Piaget’s theory of individual construction of knowledge, while conceptual models support Vygotsky’s theory of socially constructed knowledge.

The role of visualizations in cognition is of interest to cognitive scientists and psychologists. Visual-spatial skills may be referred to as visual-spatial thinking, visual literacy, visual-spatial abilities, or spatial abilities. This study is interested in the areas of visual-spatial thinking and visual literacy. Visual-spatial thinking is defined as “a complex

of intellectual skills including visual perception, image formation and storage, image manipulation, and a variety of logical and creative skills focused on image processing” (McCormack, 2002)(p.1). Averginou and Ericson (1997) cite Hortin’s (1983) definition of visual literacy as ”the ability to understand (read) and use (write) images and to think and learn in terms of images, ie, to think visually” (p. 281).Both visual-spatial thinking and visual literacy involve the use of images, visual perception, and thinking skills to process information presented visually for learning purposes.

Many scientists use visual imagery to develop and communicate their scientific ideas (Baker & Piburn, 1997; Mathewson, 1999). As Wu and Shah (2004) explain “chemistry is a visual science” (p. 465). Numerous research studies have found that chemists use a variety of visual representations to communicate and solve problems with other chemists (Habraken, 2004; Kozma, Chin, Russell, & Marx, 2000; Wu & Shah, 2004). According to Habraken (2004) visual representations are more than just communication tools; they are “...a way of thinking and the dominant way of thinking” (p.90). An understanding of visual-spatial thinking skills is useful in understanding the development of learners’ mental models.

Science education research has explored the ideas of alternative frameworks, misconceptions, or naïve conceptions since the 1970’s. Much of the early research in this area dealt with the identification and description of these alternative ideas. More recent research studies have investigated the effectiveness of various instructional strategies in changing these alternative ideas (Vosniadou, 1999). Though described in a variety of ways, conceptual change is commonly understood as dealing with the restructuring of existing knowledge based on new information (Duit, 1999). The research on conceptual change has

evolved from the idea that old knowledge is totally replaced by new knowledge (Hallden, 1999; Schnotz & Preuss, 1999) to one of gradual transformation of knowledge (Johassen, Strobel, & Gottdenker, 2005).

Initial theories of conceptual change focused heavily on the individual's role in knowledge construction, while more recent theories incorporate other aspects such as the social and cultural nature of cognition (Duit, 1999). Conceptual change has gradually become viewed as the result of interactions between an individual's mental models and consensual conceptual models (Saljo, 1999). Hallden (1999) addresses the idea of situatedness of knowledge and its impact on conceptual change. Hallden (1999) also describes three contexts in which understanding may occur: 1) situational context; 2) cognitive context; and 3) cultural context. This idea of context affecting conceptual change is important in understanding how learners' mental models may or may not change (Duit, 1999).

Chemistry can be taught at three distinct levels of representation: macroscopic, microscopic, and symbolic. The macroscopic level refers to observable chemical processes. The microscopic level is explained by the arrangement and motion of particles. The symbolic level consists of symbols, equations, formulas, and structures (Wu, Krajcik, & Soloway, 2001). Johnstone (1991) describes these levels of chemistry as a triangle with each point representing one of the above levels of representation. He suggests that one of the difficulties in learning science can be explained by this triangle. All too often teachers focus on the middle of the triangle, where all three levels interact. Meanwhile, students are usually stuck focusing on the macroscopic.

Many studies have compared how expert and novice learners use these levels of visual representations in explaining and learning chemistry. The results of these studies indicate that the experts are able to move fluently between different levels of representations, while students have a harder time connecting or moving between different representations. It was also found that experts tend to link and explain representations through their conceptual understanding of chemistry, while students focus on the surface features and types of representations. These studies suggest that students' conceptual understanding of chemistry can be improved by providing ways for students to learn to understand and relate the multiple representations (Hinton & Nakhleh, 2000; Kozma, 2000, 2003; Kozma et al., 2000; Kozma & Russell, 1997; Williamson & Abraham, 1995). Many different methods have been suggested for improving students' abilities to move between different representations, therefore increasing their conceptual understanding of chemical concepts. One particular suggestion has been to focus on teaching the particulate nature of matter. This method would emphasize the microscopic level, while including at least one of the other levels of representation. Studies on this teaching method indicate that students make significant gains in achievement when the particulate nature of matter method is used (Bunce & Gabel, 2002; Gabel, 1993). Nakhleh (1992) explains how students' insufficient understanding of the particulate nature of matter leads to several chemical misconceptions. Examples of the chemical concepts she describes as dependent upon an understanding of the particulate nature of matter include: molecules and atoms, molecules and intermolecular forces, phase changes, states of matter, chemical equations, chemical change, and chemical equilibrium. Based on

the results of the studies cited by Nakhleh, it is evident that most chemistry students, regardless of grade level, have difficulty understanding the different level of representations.

The particulate nature of matter (PNM), a central idea in science, is based upon the idea that matter is discontinuous and made of discrete particles that are in constant motion (Nakhleh, 1992; Snir, Smith, & Raz, 2003). Many of the difficulties experienced by chemistry students in understanding concepts such as chemical reactions, behavior of gases, dissolution, and equilibrium are attributed to students' lack of understanding of the particulate nature of matter model (Nakhleh, 1992). Numerous research studies have found positive results in which focusing on the particulate nature of matter has increased students' conceptual understanding and problem solving abilities in chemistry (Bunce & Gabel, 2002; Gabel, 1993; Snir et al., 2003; Westbrook & Marek, 1991; Williamson & Abraham, 1995).

The process of dissolution is an important chemistry concept and understanding of this topic has been widely researched. In their review of solution chemistry studies, Calyk, Ayas, and Ebenezer (2005) discuss methodologies used and the knowledge claims of previous solution chemistry research studies. Knowledge claims made by researchers include students 1) attending to mechanical events (Preito, Blanco, & Rodriguez, 1989), 2) preference for everyday language over chemical language (especially the usage of the term "melting" when explaining dissolving) (Ebenezer, 2001; Ebenezer & Erickson, 1996; Longden, Black, & Solomon, 1991; Preito et al., 1989), 3) confusing solution chemistry with non-related topics, such as density, chemical changes, and absorption (Ebenezer, 2001; Ebenezer & Erickson, 1996; Ebenezer & Fraser, 2001; Fensham & Fensham, 1987; Liu & Lesniak, 2006; Longden et al., 1991; Preito et al., 1989), 4) lack of sub-microscopic

explanations for macroscopic observations (Abraham, Williamson, & Westbrook, 1994; Ebenezer & Erickson, 1996; Fensham & Fensham, 1987; Preto et al., 1989), 5) difficulty with visualizing and representing sub-microscopic ideas (Ebenezer & Erickson, 1996; Harrison & Treagust, 2002; Johnstone, 1991; Preto et al., 1989; Raviolo, 2001; Treagust, Chittleborough, & Mamiala, 2003), 6) difficulty with symbolic representations (Smith & Metz, 1996), 7) inconsistent explanations (Ebenezer & Fraser, 2001), 8) development of student understanding with age (Abraham et al., 1994; Liu & Lesniak, 2006; Longden et al., 1991; Preto et al., 1989), and 9) development of conservation reasoning with age (Liu & Lesniak, 2006).

Many of the studies on solution chemistry have focused on high school aged students (Boo & Watson, 2001; Ebenezer & Erickson, 1996; Ebenezer & Gaskell, 1995; Fensham & Fensham, 1987). Several studies have focused on college chemistry students' understanding of dissolution (Ebenezer & Fraser, 2001; Kelly & Jones, 2007; Pinarbasi & Canpolat, 2003; Tien, Teichert, & Rickey, 2007). This is to be expected since it has been shown that development of the understanding of the particulate nature of matter increases with age, and understanding of dissolution is dependent upon a firm grasp of the particulate nature of matter (Longden et al., 1991). Several studies have included cross-age or cross-grade samples in an effort to better understand the progression or development of understanding (Abraham et al., 1994; Muammer Calik, 2005; Muammer Calik & Ayas, 2005; Liu & Lesniak, 2006). Calik, Ayas, and Coll (2007) in their study of the conceptual understanding of solution chemistry in pre-service elementary teachers discuss the dearth of studies involving pre-service teachers.

Research Questions

Given the widespread acceptance of constructivist and cognitive psychology theories in educational circles, the areas of conceptual understanding and learner's mental models are common topics of current educational research. As stated by Calik et al. (2007), there have been many studies in the area of solution chemistry, but almost none focus on the ideas, models, and conceptions held by pre-service teachers. The current study attempts to address this gap in knowledge by exploring the mental models of dissolution held by pre-service science teachers who have completed at least one year of college chemistry. As previously stated, pre-service teachers represent a unique population as they are transitioning between learners and teachers. This study differs from Calik et al. (2007) by focusing on pre-service teachers who are preparing to teach high-school level science, rather than elementary school. Given the differences in licensure areas, it is assumed that the subjects in the current study have a stronger science background and a higher level of interest in science than the pre-service elementary teachers in Calik's study. This research study will address the following questions:

1. What mental models do pre-service science teachers hold about the process of dissolution?
2. What mental models do pre-service science teachers hold about precipitation reactions?

CHAPTER 2
LITERATURE REVIEW

Introduction

During the 1980's some chemical educators began questioning the assumption that students' abilities to correctly solve quantitative problems equated to students' understanding of the molecular concepts underlying those problems. During this time several studies were completed that identified significant differences in students' abilities to successfully answer quantitative problems and conceptual questions in chemistry. Results of these studies suggested that chemistry students were more likely to correctly answer quantitative problems than qualitative, or conceptual, questions. The studies implied that chemical educators needed to examine their stance on focusing solely on the quantitative aspects of chemistry and instead focus their teaching and assessment strategies on both the quantitative and qualitative aspects of the subject (Lythcott, 1990; Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990). During this same timeframe, research efforts to probe students' conceptions in the field of chemistry increased and resulted in the identification of a large number of misconceptions commonly held by students (Nakhleh, 1992).

Research on chemical misconceptions was based upon the cognitive model of learning, and more recently, the research on model-based learning and teaching in science education also builds upon the area of cognition (Clement, 2000; Gobert & Buckley, 2000; Greca & Moreira, 2000; Nakhleh, 1992). One of the underlying cognitive themes in model-based research is that individuals develop their own mental models, while conceptual models are developed by researchers and educators. Learners' mental models are internal representations that can be evaluated and revised (Gobert & Buckley, 2000). On the other hand, conceptual models are external representations agreed upon by a larger community

(Greca &Moreira, 2000). Educators suspect that successful use of conceptual models in teaching may lead to increased conceptual understanding in learners (Clement, 2000). The purpose of this study is to identify mental models held by pre-service science teachers about the processes of dissolution and precipitation reactions.

Constructivism

This study is informed by the researcher's relativist perspective of epistemology and a corresponding constructivist educational philosophy. Epistemology is a branch of philosophy concerned with the nature of knowledge. Two frequently discussed epistemological perspectives in education are positivism and relativism. These two perspectives are often seen as opposite ends of the spectrum in terms of their views of reality and knowledge and how that knowledge is gained. Positivists subscribe to the belief that knowledge exists outside of the learner and that this knowledge is learned through transmission from one individual to another. Relativists, on the other hand, believe that knowledge is constructed by each individual learner rather than transmitted uniformly. While a positivist view is closely aligned with a behaviorist educational philosophy, a relativist viewpoint aligns with the constructivist educational philosophy(Hannafin & Hill, 2002).

Matthews (2000) states that constructivism is the major theoretical influence in mathematics and science education and "few would dispute Peter Fensham's claim that 'The most conspicuous psychological influence on curriculum thinking in science since 1980 has been the constructivist view of learning' (Fensham 1992, p.801)". Constructivism has become a broad umbrella term used to describe a wide variety of educational philosophies and theories. The most basic premise of all variants of constructivism is that learners

construct their own understanding. Although the many diverse views of constructivism share some similarities and differences, they all seem to agree with the general view that “(1) learning is an active process of constructing rather than acquiring knowledge, and (2) instruction is a process of supporting that construction rather than communicating knowledge” (Duffy & Cunningham, 1996, p. 171).

Duffy and Cunningham (1996) in their review of the philosophical underpinnings of constructivism cite the influence of many philosophers including Jean Jaques Rousseau, John Dewey, and Jerome Bruner on constructivism. Rousseau stressed learning by doing where the teacher’s role is one of presenting problems to stimulate curiosity and promote learning. Similar to Rousseau, John Dewey opposed the traditional school of thought that learning should focus on memorization and recitation and strongly supported learning by doing. Jerome Bruner in his emphasis on discovery learning followed in the steps of Rousseau and Dewey by viewing learning as the activity of the learner.

The works of Jean Piaget and Les Vygotsky are frequently cited as foundational for many constructivist philosophies. Many researchers believe that constructivist viewpoints can be divided into one of two categories – learning as an individual activity or learning as social activity (Abdal-Haqq, 1998; Driver, Asoko, Leach, Mortimer, & Scott, 1994; Duffy & Cunningham, 1996; Lowenthal & Muth, 2008; Mathews, 2000; Scott, Asoko, & Leach, 2007). The individual approach is frequently based upon Piagetian theory and emphasizes the construction of understanding by the individual learner. Concepts central to understanding Piaget’s theory are cognitive structure, cognitive function, and cognitive content. “Cognitive structures are identifiable patterns of physical or mental action that

underlie specific acts of intelligence” (Bybee & Sund, 1982, p. 34). These cognitive structures are described by Piaget in his each of his stages of development - sensorimotor, preoperational, concrete operational, and formal operational. Cognitive functioning is the process by which changes in cognitive structures are accounted. Cognitive functioning involves both the organization and adaptation of cognitive structures. Piaget’s concepts of assimilation and accommodation are central to cognitive functioning. Cognitive structures and functioning must be inferred from the observable actions of the learner. Cognitive content is the motoric or cognitive actions that are called intelligent and are clearly and directly observable (Bybee & Sund, 1982).

Although Piaget did not refer to himself as a constructivist until much later in his life, the idea that knowledge is constructed by the adaptation of cognitive structures through cognitive functioning is essential to his theory. In order for learning to occur, equilibration at the individual level is necessary (Bybee & Sund, 1982; Driver et al., 1994; Duffy & Cunningham, 1996). Piaget acknowledged the role social interaction could play in cognitive development, but his primary viewpoint was that cognitive development was primarily a function of the individual’s experiences (Driver et al., 1994).

The social view of constructivism is based on the belief that knowledge is constructed by individuals but in a social context and is rooted in the work Lev Vygotsky (Abdal-Haqq, 1998; Driver et al., 1994; Duffy & Cunningham, 1996). Vygotsky asserts that individual development is social in nature and is mediated through the use of language with other members of the community. Driver et al. (1994) describe the social view of constructivism as “...individuals engage socially in talk and activity about shared problems or tasks. Making

meaning is thus a dialogic process involving persons-in-conversation, and learning is seen as the process by which individuals are introduced to a culture by more skilled members.” (p.7)

Both individual and social constructivism rely heavily upon students’ experiences, however, as Matthews (2000) asserts many of the realms of science exist outside of the reach of a science classroom. Thus it is quite difficult to provide experiences in the atomic, astronomical, and cellular realms of science. One strategy for providing experiences in these areas is through the use of technologies, such as videos, animations and simulations, to assist learners in visualizing these topics and gaining experiences with multiple levels of representation. Before discussing the role of multiple representations, it may be helpful to understand the role of models and visualization in learning as described by cognitive science and psychology.

Cognitive Science and Psychology

Cognitive science is defined in the Merriam-Webster Online Dictionary ("cognitive science," 2010) as “an interdisciplinary science that draws on many fields (as psychology, artificial intelligence, linguistics, and philosophy) in developing theories about human perception, thinking, and learning.” Hestenes (2006) describes the emergence of the field of cognitive science and breaks it down into two generations. The first generation of cognitive science developed between the 1960’s and early 1980’s. During this time, the brain was frequently viewed as a computer leading to the creation of information processing psychology. In information processing, thinking was described as the manipulation or processing of symbols. Biological details about the brain and its function were not considered relevant. This train of thought was and remains a central idea in the areas of

computer science and artificial intelligence. The second generation of cognitive science arose around 1983 and is now known as cognitive neuroscience. This generation of cognitive science seeks to link cognitive theory from psychology with the neural network theory and the sensory motor system at the biological level. In this generation thinking is described as the processing of patterns (Hestenes, 2006).

Numerous researchers have discussed the importance of the contributions of cognitive science and psychology to our understanding of the processes of learning and instruction, especially in the areas of model-based teaching and learning (Clement, 2000; Gobert & Buckley, 2000; Greca & Moreira, 2000; Hestenes, 2006; Matthews, 2007a). The following sections will review how the theories of modeling, specifically mental and conceptual models, are related to cognitive science and how they influence our current understanding of conceptual learning.

Models

Models have long been important to scientists in all disciplines. One only has to open any science textbook and the use of models by scientists is apparent in the many references to currently accepted and historic models such as the double-helix model of DNA, the particle model of light, the plate tectonic model, and the plum-pudding model of the atom (Matthews, 2007b). Generally, a model is defined as a representation of a phenomenon, an object, or an idea (Gilbert, Boulter, & Elmer, 2000). Models are also considered "...simplified representations of a system, which concentrates attention on specific aspects of the system" (p. 891). Tregidgo and Ratcliffe (2000) define models in science as the representation of a phenomenon, object or idea (the target) with a more familiar one (the source). There are

many different types of models and the words used to categorize them can vary from researcher to researcher (Greca & Moreira, 2000; Harrison & Treagust, 2000; Johnson-Laird, 1983; Norman, 1983). Two categories of models that are relevant to the current study and are widely recognized in education literature are mental models and conceptual models. Mental models are internal representations created by individuals in their minds, while conceptual models are external representations created through consensus from various experts (Greca & Moreira, 2000). Each category is described in the following sections.

Mental models.

Psychologist Kenneth Craik is frequently cited as the person responsible for the modern idea of mental models. In his 1943 book *The Nature of Explanations*, Craik suggested that thinking is the result of manipulating internal representations of the world and that human beings are processors of information. He also described three processes in reasoning:

- 1) A 'translation' of some external process into an internal representation in terms of words, numbers, or other symbols.
- 2) The derivation of other symbols from them by some sort of inferential process.
- 3) A 'retranslation' of these symbols into actions, or at least a recognition of the correspondence between these symbols and external events, as in realizing that a prediction is fulfilled. p.2-3 (Johnson-Laird, 1983)

Although the computer had not yet been invented, Craik's theory supports an analogy between computers and the human brain. Craik's theory was foundational to the first generation of cognitive science which viewed thinking as the processing of symbols and information.

Phillip Johnson-Laird built upon Craik's work by theorizing about mental models and their relationship to understanding. According to Johnson-Laird (1983), the psychological core of understanding is to have a "working model" of a phenomenon in the mind. Johnson-Laird used data from the research of others and computer modeling to make the case for the existence of mental models and the development of a coherent theory of mental models and the role of mental models in learners' understanding in his book *The Nature of Mental Models*. The overwhelming acceptance of Johnson-Laird's theory is evidenced by the numerous citations of his work by most researchers interested in the idea of mental models.

Here are several essential ideas about the nature of mental models as explained by Johnson-Laird (1983): "There are no complete mental models for any empirical phenomena."

(p. 4) – Johnson-Laird claims that the usefulness of a mental model is not necessarily increased by adding additional information and details beyond a certain point.

"Many mental models are little more than high-grade simulations...all representations of physical phenomena necessarily contain an element of simulation." (p. 4). Mental models are recursive, meaning mental models are dynamic and new information can be incorporated into existing models. The concept of recursiveness helps to explain comprehension of discourse and how discourse can lead to changes in understanding by an individual. In the final chapter of his book, Johnson-Laird summarizes this theory on the role and nature of mental models as corroborated by his computer modeling and investigations:

It is now plausible to suppose that mental models play a central and unifying role in representing objects, states of affairs, sequences of events, the way the world is, and the social and psychological actions of daily life. They enable individuals to make inferences and predictions, to understand phenomena, to decide what action to take and to control its execution, and above all to experience events by proxy; they allow

language to be used to create representations comparable to those deriving from direct acquaintance with the world; and they relate words to the world by way of conception and perception. (p. 397)

Johnson-Laird (1983) devotes an entire chapter of his book to the relationship between mental models, images, and propositions. He argues that images are special classes of models. He acknowledges the conscious phenomenon of imagery and how people use their imagination to form visual images of objects or scenes. Citing the works of other psychologists, Johnson-Laird (1983) describes some of the characteristics of these mental images:

Such images can be mentally rotated at a rate of about sixty degrees per second (Shepard, 1978); they can be suppressed by concurrent visual tasks (Brook, 1967); they can be used to represent spatial information and to solve problems (Kosslyn, 1980); they are a useful aid to memory (Pavio, 1971; Bower, 1972). (p 146-147)

Johnson-Laird describes the consensus among these psychologists in the argument that images are a distinct type of mental representation. The four point of consensus are listed below:

1. The mental processes underlying the experience of an image are similar to those underlying the perception of an object or picture.
- 2) An image is a coherent and integrated representation of a scene or object from a particular viewpoint in which each perceptible element occurs only once with all such elements being simultaneously available and open to a perception-like process of scanning.
- 3) An image is amenable to apparently continuous mental transformations, such as rotations or expansions, in which intermediate states correspond to intermediate states (or views) of an actual object undergoing the corresponding physical transformation. Hence, a small change in the image corresponds to a small change (of view) of the object.
- 4) Images *represent* objects. They are analogical in that structural relations between their parts correspond to the perceptible relations between the parts of the objects represented. (p. 147)

As Johnson-Laird believes that images are a special class of mental models, then it can be argued that the points above about images could also apply to the larger category of mental models.

Donald Norman is also frequently cited for his work in the area of mental models. The major difference between the work of Johnson-Laird and Norman is their approaches – Johnson-Laird's is a theoretical approach to mental models, while Norman's is an instructional approach (Greca & Moreira, 2000). Similar to Johnson-Laird, Norman (1983) states that mental models are internal representations developed by individuals representing the individual and the things he or she is interacting with. Below are Norman's (1983) essential ideas about mental models:

1. Mental models are incomplete.
2. People's abilities to "run" their mental models are severely limited.
3. Mental models are unstable: People forget the details of the system they are using, especially when those details (or the whole system) have not been used for some period.
4. Mental models do not have firm boundaries: similar devices and operations get confused with one another.
5. Mental models are "unscientific": People maintain "superstitious" behavior patterns even when they know they are unneeded because they cost little in physical effort and save mental effort.
6. Mental models are parsimonious: Often people do extra physical operations rather than the mental planning that would allow them to avoid those actions; they are willing to trade-off extra physical action for reduced mental complexity. (p. 8)

Norman (1983) also stresses the four things to be considered when discussing mental models – the target system, the mental model, the conceptual model, and the scientist's conceptualization. The target system is that which the individual is learning or using. The mental model is the individual's personal model of the target system. These models are evolving and will continue to be modified by interaction with the target system. Mental

models are constrained by the individual's previous experiences, technical background, and the capabilities of the human brain for processing information. The conceptual model is invented by educators, scientists, and engineers and is considered accurate, consistent, and complete. The scientist's conceptualization is a model of a model and is usually more detailed and complex than the conceptual model.

The concept of mental models from Craik, Johnson-Laird, and Norman support Piaget's work on how individuals learn. Other researchers interested in model-based learning also link key components of Piaget's work, such as the existence of schema, to the existence of mental models (Seel, 2003; Taber, 2000). Seel (2003) states that "schemata also form the basis of the construction of models, which can be understood in accordance with Piaget as 'tools' of accommodation" (p. 63). While Johnson-Laird and Norman also acknowledge the social role in learning, both describe mental models as constructions created by each individual and that learning occurs through the constant revisioning of these constructions. Numerous researchers building upon the works of the cognitive scientists previously described have argued that the ability to form mental models is an essential characteristic of the human cognitive system and the development and use of these models by individuals is critical to learning (Clement, 2000; Gobert & Buckley, 2000; Greca & Moreira, 2000; Harrison & Treagust, 2000; Hestenes, 2006; Ornek, 2008; Taber, 2000; Vosniadou, 2002).

Conceptual models.

As mentioned earlier, conceptual models differ from mental models in that they are considered consensus models rather than individual models. Norman (1983) defines

conceptual models as tools created for the teaching of physical systems. He further describes conceptual models as complete representations that are coherent with scientifically accepted knowledge. Greca and Moreira (2000) define conceptual models as "...an external representation created by researchers, teachers, engineers, etc., that facilitates the comprehension or the teaching of systems or states of affairs in the world" (p. 5). Ornek (2008) defines conceptual models as "...simplified and idealized representations of real objects, phenomena, or situations" (p. 45). Mathematical models, computer models, physical models, and analogies are all types of conceptual models (Greca & Moreira, 2000; Ornek, 2008). Based on these descriptions of conceptual models, one can see how the development of conceptual models supports Vygotsky's theory on the social nature of learning.

The relationship between conceptual models and mental models is extremely important from an instructional viewpoint. Norman (1983) stresses that "there ought to be a direct and simple relationship between the conceptual and the mental model. All too often, however, this is not the case." Perhaps Hestenes (2006) in his development of a modeling theory of science, cognition and instruction best explains the relationship between conceptual and mental models. Figure 2.1 is a reproduction of his figure illustrating the relationship between mental and conceptual models. Greca and Moreira (2000) discuss the common assumption of educators that students construct mental models that are copies of the conceptual models presented to them. Numerous science educators and researchers suspect that conceptual models are important in aiding learners' to reach conceptual understanding, which is discussed in greater detail in a following section (Clement, 2000).

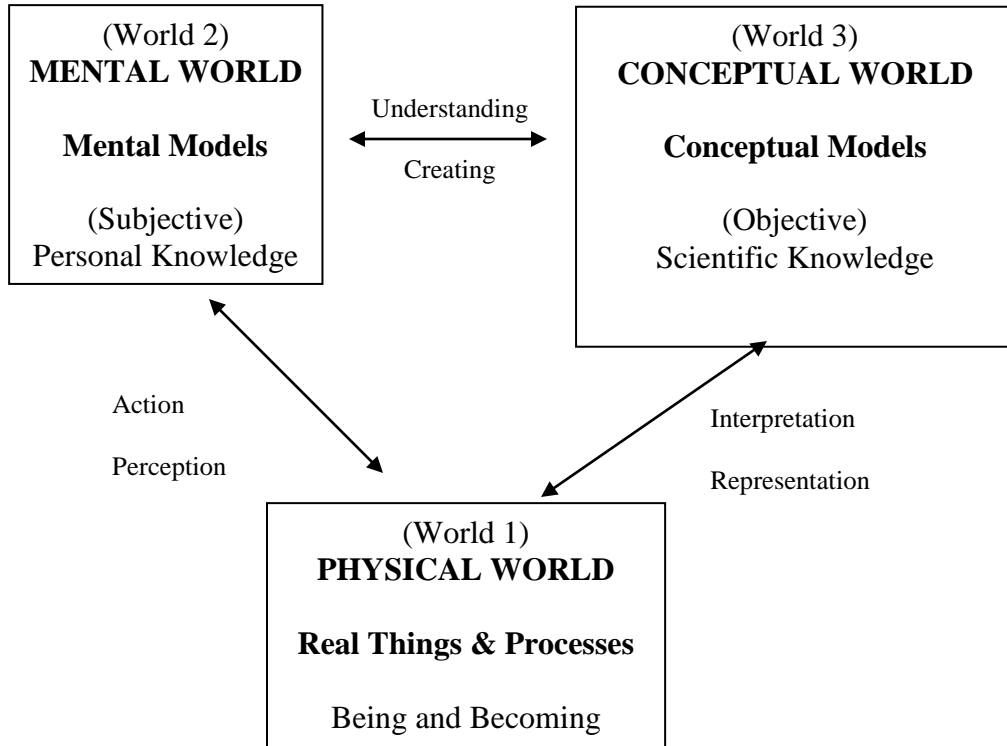


Figure 2.1. Mental models versus Conceptual models

Visual-Spatial Thinking Skills

Cognitive science and psychology also are interested in the role of visualizations in cognition. Visual-spatial skills have been defined and described in a variety of ways. They may be referred to as visual-spatial thinking, visual literacy, visual-spatial abilities or spatial abilities. McCormack (2002) defines visual spatial thinking as “a complex of intellectual skills including visual perception, image formation and storage, image manipulation, and a variety of logical and creative skills focused on image processing” (p.1). Mathewson (1999) explains that visual-spatial thinking is dependent upon both “... vision – the process of using the eyes to identify, locate, and think about objects and orient ourselves in the world, and

imagery – the formation, inspection, transformation, and maintenance of images in the ‘mind’s eye’ in the absences of visual stimulus.” (p. 34). In a review of visual literacy literature, Averginou and Ericson (1997) cite Hortin’s (1983) definition of visual literacy as ”the ability to understand (read) and use (write) images and to think and learn in terms of images, ie, to think visually” (p. 281). Visual-spatial abilities are multi-faceted skills that involve many factors. Despite the numerous names and descriptions given to these visual-spatial abilities, they all involve the use of images, visual perception, and thinking skills to process information presented visually for learning purposes.

The importance of visual-spatial thinking skills in classrooms, especially science, has been implied in many research papers (Arnheim, 1993; Avgerinou & Ericson, 1997; Carter, LaRussa, & Bodner, 1987; Eisner, 1993; Furby, 1971; Kotulak, 2000; Massironi, 2002; Mathewson, 1999; McArthur & Wellner, 1996; McCormack, 2002; Piburn et al., 2002; Rieber, 1995; Vasu & Howe, 1989). Implications from the previous studies indicate that an increased use of visual-spatial thinking skills in the science classroom would result in better achievement for all students. Diverse learning groups who characteristically do not succeed in school could potentially benefit the most (Avgerinou & Ericson, 1997; Eisner, 1993; Furby, 1971; McCormack, 2002; Rieber, 1995). Avgerinou and Ericson (1997) reference the widely stated assumption that the visual sense is the most dominant and therefore the most important. Despite this assumption, verbal and logical-mathematical skills and teaching strategies are dominant in most educational settings (Habraken, 2004).

Visual-spatial thinking skills in science.

Most of the scientific phenomena of interest to the scientific community and therefore science education exist beyond the perceptual abilities of human beings. These phenomena can vary in size from sub-atomic particles to the heavenly bodies of the universe. Our understanding of these phenomena rests on our abilities to interact indirectly with the phenomena through the use of representations. These representations may include, but are not limited to, verbal descriptions, symbolic equations, coordinate graphs, and structural diagrams (Kozma, 2000). Scientists, such as Einstein, Tesla and Faraday used visual imagery to develop and communicate their scientific ideas. Therefore, it is not surprising that many scientists are strong visual-spatial thinkers (Baker & Piburn, 1997; Mathewson, 1999).

The role of visual-spatial thinking skills in chemical education is very important. As Wu and Shah (2004) explain “chemistry is a visual science” (p. 465). To better understand the role of visual-spatial thinking skills in learning chemistry, several researchers have studied how chemists use visualizations in their work. In these studies, it is noted that chemists use a variety of visual representations to communicate and solve problems with other chemists (Habraken, 2004; Kozma et al., 2000; Wu & Shah, 2004). The representations used by chemists include, but are not limited to, symbols, formulas, equations, molecular models, graphs, and molecular animations (Kozma et al., 2000; Wu & Shah, 2004). Habraken (2004) contends that visual representations are more than just communication tools for chemists; that in fact they are “...a way of thinking and the dominant way of thinking” (p.90).

Conceptual Change

Since the 1970's, science educators have acknowledged that students bring alternative frameworks, misconceptions, or naive conceptions to the science classroom. These alternative ideas are typically based on students' everyday experiences and are quite resistant to change through most teaching strategies. Early research on the identification of these misconceptions or alternative conceptions eventually led to research on instructional strategies for addressing these misconceptions and the development of a conceptual change theory (Vosniadou, 1999).

As is the case with many terms in education, the phrase conceptual change has a variety of meanings. The mainstream agreement is that conceptual change has to do the restructuring of existing knowledge based on new information (Duit, 1999). Some of the early research on conceptual change stated that old knowledge was totally replaced by new, more accurate knowledge (Hallden, 1999; Schnotz & Preuss, 1999). Jonassen, Stroel and Gottdenker (2005) define conceptual change as what happens when learners change their understanding of concepts and the conceptual frameworks that encompass those concepts. They also explain how conceptual change is described as an evolutionary process of gradual transformation of knowledge by some researchers, while other researchers describe the process as revolutionary resulting from cognitive conflict. The idea of cognitive conflict as related to conceptual change is credited to Strike and Posner (Johassen et al., 2005).

Strike and Posner, in their initial conceptual change theory, as cited by numerous researchers state that four conditions must exist in order for conceptual change to take place. Those conditions are: 1) the learner must be dissatisfied with the current conception; 2) the

new conception must be intelligible; 3) the new conception must appear plausible; and 4) the new conception must be fruitful (Duit, 1999; Schnotz & Preuss, 1999; Trowbridge, 2000; Vosniadou, 1999). Strike and Posner's initial theory was heavily based on Piaget's theory of intellectual development, which stressed the reorganization of knowledge or cognitive structures. According to Piaget, the human mind inherently tends toward equilibration, or the reduction of cognitive conflict. Piaget theorizes that equilibration is made possible through the processes of assimilation and accommodation (Bybee & Sund, 1982; Trowbridge, 2000).

Piaget frequently referred to the concept of schema in his theory of intellectual development and that concept is considered central to the study of modern cognitive psychology (Seel, 2003). Schemata, often called the basic building blocks of cognition, are defined as cognitive structures in which general knowledge is represented in memory. Piaget theorizes that schemata serve to assimilate new information into existing knowledge structures to promote equilibration (Bybee & Sund, 1982; Schnotz & Preuss, 1999; Seel, 2003). Seel (2003) also states that these schemata are the basis for the construction of mental models. Saljo (1999) states that the terms mental models, representations, and schemas are entities with the same ontological status as concepts and cognitive structures. For the purpose of this study, this statement will be assumed to be true and the terms from hereon will be used interchangeably.

Strike and Posner's initial theory of conceptual change was criticized for focusing solely on the individual's role in knowledge construction. Researchers then sought to incorporate other aspects, such as the social and cultural nature of cognition, into theories on conceptual change (Duit, 1999). Building on the works of Bruner and Vygotsky, researchers

began to view conceptual change as the result of the interaction between individual's mental models and consensual conceptual models (Saljo, 1999). According to Schnotz and Preuss (1999), Vygotsky argued that the problem in integrating learners' prior knowledge with scientific knowledge was the result of naïve conceptions based on everyday experiences belonging to different conceptual systems than the scientific concepts taught in school. The purpose of school and teaching was to mediate or help bring these different systems together so that the two could be integrated (Saljo, 1999; Schnotz & Preuss, 1999).

Several researchers have discussed the idea of the situatedness of knowledge and how this can impact conceptual change. Hallden (1999) in his discussion on the role of contextualization on conceptual change describes at least three different processes that may be signified by conceptual change. The first process is the abandoning of old conceptions and replacement with new conceptions, as in cognitive development. The second process involves the acquisition of an entirely new conception. The third process entails the enrichment of existing conceptualizations, instead of creating new conceptions or replacing old conceptions, new information is integrated into existing knowledge structures. The context in which the learning is taking place determines which of these three processes occur.

Hallden (1999) also identifies three contexts in which science understanding may occur. Situational context, or everyday settings, is commonly encountered by science educators and researchers when learners situate the task or problem at hand in an everyday context and find scientific explanations inappropriate. The second context is called cognitive context and is frequently encountered when introducing learners to new subject matter. The final context is identified as cultural context and relates to speech genre. In this final context,

as learners move more towards experts in a specific field, they must be introduced to the appropriate speech to assist in the further refining of their conceptualizations. The idea of context affecting conceptual change is important as one begins to research the mental models held by learners and how these mental models may or may not change (Duit, 1999).

Several researchers have theorized about how learners may appear to hold multiple representations of the same concept depending upon the context (Duit, 1999; Pozo, Gomez, & Sanz, 1999; Saljo, 1999; Schnotz & Preuss, 1999; Vosniadou, 1999). Based on this theory, part of the problem in science education is that teachers and researchers may think that learners' naïve conceptions and misconceptions must be replaced by scientifically accurate conceptions. Instead, teaching should focus on helping students to learn to identify the context of the task or problem at hand and how different conceptions or representations are more appropriate than others in a particular context (Duit, 1999; Pozo et al., 1999; Saljo, 1999; Schnotz & Preuss, 1999).

The idea of contextualization is valuable when attempting to understand the differences between novice and expert understanding. Much of the early conceptual change research focused on identifying the differences in conceptions between novices and experts, with those conceptions of novices being labeled alternative, naïve, or misconceptions. Using the theories of Duit (1999), Pozo et al (1999), Saljo (1999), Schnotz & Preuss (1999), and Vosniadou (1999), one can argue that experts may hold the same alternative or naïve conceptions as novices. The only difference is that experts are better at identifying the appropriate mental model or conception based upon the situation. This revised framework for understanding conceptual change builds the foundation for understanding the one of the

common difficulties in learning science, specifically chemistry, which is the use of multiple representations as described in the following section.

Difficulties in Learning Chemistry

Multiple levels of representation.

Johnstone (1991) proposes that one of the reasons students have difficulty in science is due to the multiple levels of representation at which a science topic can be examined. For example, chemistry can be taught at three distinct levels of representation: macroscopic, microscopic, and symbolic. The macroscopic level refers to observable chemical processes. The microscopic level is explained by the arrangement and motion of particles. The symbolic level consists of symbols, equations, formulas, and structures (Wu et al., 2001; Wu & Shah, 2004). Johnstone (1991) describes these levels of chemistry as a triangle with each point representing one of the above levels of representation. He suggests that one of the difficulties in learning science can be explained by this triangle. All too often teachers move within the middle of the triangle, where all three levels interact and are connected. Meanwhile, students generally focus on only one level, usually the macroscopic. Figure 2.2 represents the three levels of representation in chemistry.

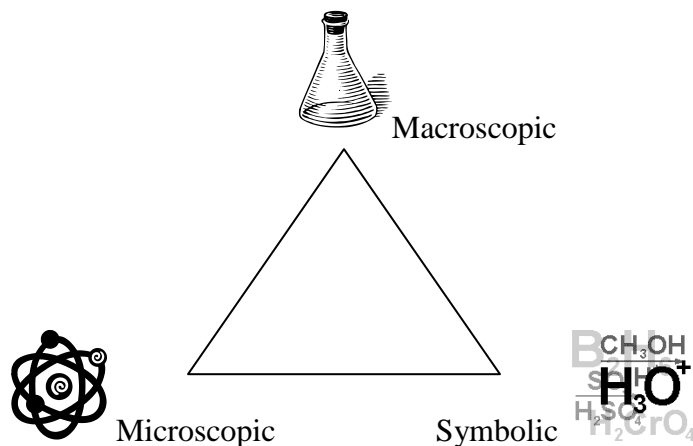


Figure 2.2. Johnstone's Triangle of Chemical Representations

Gabel (1993) suggests several reasons students have difficulty in developing conceptual understanding in chemistry. Two of the reasons provided relate directly to Johnstone's theory of multiple levels of representation. The first explanation that Gabel (1993) proposes is that chemistry teachers "...emphasize the symbolic level and problem-solving at the expense of the phenomena and particle levels." (p. 193). Her second explanation is that "...even though it (chemistry) is taught at three levels, insufficient connections are made between the three levels..." (p. 193).

Expert vs. novice use of multiple levels of representation.

Numerous studies have researched the similarities and differences between experts (professional chemists) and novices (chemistry students) and their uses of multiple chemical representations. In 1997 (Kozma & Russell), a group of novices and experts were given cards of multiple representations of chemical equilibrium phenomena and asked to group the representations in a way that made sense to them. In this particular study the novice group consisted of undergraduate college students enrolled in first-semester chemistry. The experts

consisted of a group of professional chemists working in labs, chemists teaching at the college level and doctoral students in chemistry. The results of this task indicate that experts were able to chunk larger amounts of information together in meaningful patterns. While the novices were able to group the representations, they frequently created smaller groupings than the experts, and subsequently, created a larger quantity of groupings. In an analysis of the participants' reasons for their groupings, the experts overwhelmingly relied on conceptual understanding whereas novices mostly relied on surface features of the representations.

In the same study, Kozma and Russell (1997) asked the participants to transform one type of chemical representation into a corresponding type of representation. The expert group had a higher percentage of correct transformations than the novice group. The researchers propose that experts exhibit representational competence which can be described as the ability to understand that representations with different surface features can represent the same chemical phenomenon and the ability to transform one chemical representation into another representation correctly.

In a later study, Kozma (2003) again researched the differences between experts and novices in the use of chemical representations. This time the participants were involved in naturalistic studies to complement the earlier experimental studies. For the naturalistic studies, the research observed and interviewed the participants in authentic settings. For the experts, this setting included a pharmaceutical laboratory and a university academic laboratory involved in the synthesis of compounds. For the novices, this setting was an undergraduate organic chemistry laboratory in which the task was to synthesize chemical compounds. It was found that experts use multiple representations to reason and

communicate with others about the task at hand. Experts move fluently between multiple representations and use "...the features of the representations to support their discourse about the entities and processes..." (p. 213). The novices were more focused on the lab equipment and procedures. Most of the novice talk was related to asking or giving help on the procedure.

The results of expert-novice studies suggest that an increased ability to use multiple representations results in a better understanding of chemical phenomena. Experts have mastered this ability and use it frequently to communicate with other chemists, while novices have not mastered this ability. Mastering this ability is essential in developing a strong conceptual understanding of chemical phenomena (Kozma, 2003; Kozma et al., 2000; R. B. Kozma & J. W. Russell, 1997).

The particulate nature of matter.

The particulate nature of matter is considered a central idea in science. It is based upon the notion that matter is discontinuous and made of discrete particles that are in constant motion (Nakhleh, 1992; Snir et al., 2003). Many students have difficulty in understanding and using this model of matter, which means they have a weak foundation for understanding many chemical concepts, such as, reactions, behavior of gases, phase changes, dissolution, and equilibrium (Nakhleh, 1992). Several researchers have hypothesized that emphasizing the particulate nature of matter in chemistry teaching would result in a better conceptual understanding and higher achievement in chemistry (Bunce & Gabel, 2002; Gabel, 1993; Snir et al., 2003; Williamson & Abraham, 1995).

Gabel (1993) reported that the use of static visualizations depicting the particulate nature of matter were effective in helping high school chemistry students to make connections between the three levels of representation – microscopic, macroscopic, and symbolic. In a related study, high school chemistry students were taught chemical concepts using three levels of representation – macroscopic, microscopic (particulate nature of matter), and symbolic. A control group of high school chemistry students were taught the same concepts using only macroscopic and symbolic representations. The results of this study led to the conclusion that teaching with microscopic representations results in increased chemistry achievement for female students, but not necessarily for male students. Females taught with an emphasis on the particulate nature of matter outperformed females that were not and performed at the same achievement level of males taught with an emphasis on the microscopic level (Bunce & Gabel, 2002).

Solution chemistry

Solution chemistry is an important topic in the chemistry curriculum. As such, numerous research studies related to this topic have been conducted. In their review of solution chemistry research literature, Calyk, Ayas, and Ebenezer (2005) organize the studies by concepts: dissolution, nature of solutions, solubility, energy in solution process, effects of temperature and stirring on dissolution, conservation of mass during dissolution, types of solution, vapor pressure lowering and solubility of gas in water, and strategies to overcome students' conceptions. In addition to reviewing students' conceptions, Calyk et al. (2005) also review the methods used in research studies for exploring students' conceptions. The

current study will focus only on those studies involving the dissolution of solids and reactions of ionic solids in solution.

Fensham and Fensham (1987) studied the understanding of three chemical phenomena in Indonesian high school students. The phenomena included 1) solids dissolving in water; 2) reactions between chemicals in solution; and 3) factors that influence reaction rates in solutions. Participants in this study frequently used the term “dissolve” to describe the phenomenon. They also used the term “disappear” when the solute was no longer visible. A few participants, used the term “melt” to describe the phenomenon. In their analysis of reactions between chemicals in solution, Fensham and Fensham(1987) found that grade level of the student related to the student’s ability to name the product of the reaction and refer to ions as the reacting species. None of the participants used a particulate model to explain the precipitation reaction.

Prieto, Blanco, and Rodriguez (1989) through open-ended questions and drawings studied middle school students (ages 11-14) ideas about the nature of solutions. When asked to explain dissolving one substance in another, participants in this study responded with a variety of aspects of the phenomenon. The responses were categorized as mechanical (i.e. shaking or stirring), thermal (heating), characteristics of the substance being dissolved, the role of the solvent, and the interaction of the solute and solvent. Mechanical actions were the most frequent explanations and characteristics of the solute were the second most frequent explanation. Analysis of participants’ drawings indicated that students at this age level still hold a continuous view of dissolved substances.

Abraham, Williamson, and Westbrook (1994) in their cross-age study of five chemistry concepts using middle school, high school, and college students found that while 60.7% of the students held some understanding of the process of dissolution, only 27.3 % of the participants had a sound understanding of the process. Another finding of interest in this study is that “students at all levels tended not to use atomic and molecular explanations for chemical phenomena” (p. 163).

Ebenezer and Gaskell (1995) and Ebenezer and Erickson (1996) in interviews with high school chemistry students identified six categories of students’ explanations of the process of dissolution. These categories included 1) physical transformation from solid to liquid; 2) chemical transformation of the solute; 3) density of the solute; 4) amount of space available in solution; 5) properties of the solute; and 6) size of solute.

Boo and Watson (2001) studied the progression of high school students’ understanding of solution chemistry by interviewing the same students in successive academic years. Despite using subjects considered to be successful chemistry students, the researchers identified four frequently held alternative conceptions related to dissolution. The first alternative conception held by participants is that bond breaking is exothermic and bond making is endothermic. The second alternative conception was ionic bonding results in ion pairs or some kind of covalent bond. The third alternative conception was that water (solvent) does not play any part in the dissolution process. The fourth alternative conception was the use of causal agents as the driving force in chemical reactions. These causal agents included reactive substances, differences in reactivity between substances, and heat.

Calik and Ayas (2005) assessed the understanding of middle school (ages 13-14) and high school (ages 16-17) students on the topic of chemical solutions and their components. Using a multiple choice question and open-ended questions, the researchers found that students have difficulty using the terms solution, solvent, and solute correctly. The researchers also state that students seem to confuse hydration with hydrolysis when attempting to explain how a solid dissolves. Calik (2005) in another cross-age study of students' understanding of solution chemistry discusses the students confusion between melting and dissolving. This interchanging of the terms melting and dissolving had previously been discussed by other researchers (Abraham et al., 1994; Ebenezer & Erickson, 1996; Ebenezer & Gaskell, 1995; Preto et al., 1989).

Liu and Lesniak (2006) sought to understand the progression of children's understanding of the concept of matter by interviewing students in grades 1-10. When asked to describe what happens when baking soda and water are mixed, the younger students (grades 1-6) solely focused on observable properties, such as it disappeared, for their explanations. Students in grades 7-10 use more technical terms to explain the phenomenon, but still demonstrate an incomplete understanding of dissolution.

Calik, Ayas, and Coll (2007) used written questions to assess the understanding of pre-service elementary education teachers on the topics of dissolution. The researchers cite the near absence of literature involving pre-service teachers in the studies of alternative conceptions as the reason for using this particular target sample. The finding of interest in this study is that the pre-service elementary teachers hold many of the same alternative

conceptions, such as confusing the terms melting and dissolving, as previously reported in the literature.

Tien, Teichert, and Rickey (2007) explored the molecular level ideas of college level chemistry students before and after the completion of a MORE (model-observe-reflect-explain) laboratory module. Prior to implementation of the laboratory module, many students displayed numerous incorrect ideas about the dissolution of salt in water. These alternative conceptions include 1) salt dissolves into molecular units; 2) salt dissolves into neutral atoms; 3) salt forms chemical bonds with water; and 4) salt undergoes a metathesis reaction with water. The implementation of the MORE laboratory module led to a significant reduction in the use of these alternative conceptions in students' molecular-level drawings and explanations.

CHAPTER 3
METHODOLOGY

Purpose

The purpose of this study was to identify and describe the mental models held by pre-service science teachers on the processes of dissolution and precipitation reactions. To accomplish this, participants viewed videos of four ionic solids dissolving in water and two videos of precipitation reactions using solutions from the previous videos. While watching the videos, the participants completed a questionnaire which required them to answer multiple choice questions, write chemical equations, and draw representations of the chemical phenomenon observed. The questionnaire was developed by the researcher and piloted with pre-service science teachers at two public universities to determine if modifications were needed. The following year, a different group of pre-service science teachers completed the questionnaire and an individual interview with the researcher. The interviews were conducted to gain an understanding of participants' mental reasoning while completing the questionnaire. Previous research studies on the topic of dissolution have focused primarily on populations of high school and college science students (typically in the first two years of college). Pre-service science teachers represent a unique population who are transitioning between the roles of learner and teacher. By focusing on this unique population, this study hopes to uncover information on science teachers' transition between alternative conceptions and accepted conceptual models related to dissolution and precipitation reactions.

This study will address the following questions:

1. What mental models do pre-service science teachers hold about the process of dissolution?

2. What mental models do pre-service science teachers hold about the process of precipitation reactions?

The Setting

The setting for the study was University of Southeast. (The universities and participants discussed in this study have been assigned pseudonyms to protect the identity of the participants.) The university has a population of approximately 6700 full-time and part-time undergraduate and graduate students. The university has numerous bachelors and masters degree programs in education, business, and arts and sciences disciplines. This study was conducted using junior and senior level students in the Bachelor of Science (B.S.) in Science Education program and first year students in the Masters of Arts in Teaching (M.A.T.) with 9-12 Science Specialization program. For the 2009-2010 academic year, enrollment in the Bachelor of Science in Science Education program was 28 and 10 in the Masters of Arts in Teaching with 9-12 Science Specialization. Upon completion of all requirements for the B.S. in Science Education and M.A.T. with 9-12 Science Specialization degrees, students are recommended for the comprehensive 9-12 science teaching license in North Carolina. This comprehensive license allows teachers to teach any science course offered in public high schools.

The B.S. in Science Education program, housed within the Biology Department in the College of Arts and Sciences, is a collaborative effort with the School of Education. Students in the B.S. in Science Education program complete a concentration in one of the following four science disciplines – biology, chemistry, earth science, or physics. The concentration most frequently selected by students is biology followed by earth science,

chemistry, and physics. Very few students complete the chemistry or physics concentration. In the seven years prior to the study, there were four chemistry concentration program completers and two physics concentration program completers. Each of the four concentrations require 26-28 semester hours in the specific scientific discipline, in addition to, a minimum of two semesters of introductory level coursework in the remaining three science disciplines and mathematics. All four concentrations require a minimum of two semesters of General Chemistry lectures and laboratories and one semester of Organic Chemistry lecture and laboratory. Upon completion of the B.S. in Science Education degree, all students have completed a minimum of 62 hours of science and mathematics coursework regardless of the selected concentration. In the biology, chemistry, and physics concentrations, B.S. in Science Education students may elect to double major in the specific science discipline by completing 9 – 18 additional hours of science and mathematics courses. This option is not available in the earth science concentration as the university does not offer a major in geology or earth science. Approximately 90% of the students in the B.S. in Science Education program elect to complete the requirements for the double major in the science discipline.

The M.A.T. program, housed in the School of Education, is a collaborative effort with the respective academic departments in the College of Arts and Sciences. The M.A.T. program serves as a pathway for students who have earned a bachelors degree in an academic discipline to obtain a public school teaching license while earning a masters degree. Students admitted to the M.A.T. with 9-12 Science Specialization are expected to have the equivalent science and mathematics courses as required in the B.S. in Science Education degree. Students lacking any of the undergraduate level science or mathematics courses are granted

provisional admission until they successfully complete the coursework to address the areas of deficiency. The majority of students enrolled in the M.A.T. with 9-12 Science Specialization are part-time students who currently teach public school with a lateral-entry license.

However, a small number of full-time students enter the M.A.T. with 9-12 Science Specialization program immediately upon completion of their bachelors degree and do not begin teaching until after completion of the M.A.T. program.

Subjects

Pilot study subjects.

The pilot study was conducted in spring 2009. Twenty-two pre-service science teachers enrolled in two public universities participated in the pilot study. University of Southeast is a mid-sized masters University of Southeast were seeking high school level science licensure. Eight of the fourteen participants from University of Northeast were seeking high school level science licensure, and the remaining six Northeast participants were seeking middle grades science licensure. Both universities offer undergraduate programs leading to teacher licensure in the areas of middle grades and high school science. All pilot study participants were enrolled in a junior level science education methods courses at each institution.

Study subjects.

This study was conducted in summer 2010. Based on results of the pilot study, the researcher limited this study to 12 participants so that each participant could be individually interviewed after completing the questionnaire. Participants were selected using a combination of purposive and convenience sampling. At the time of the study, the researcher

was employed as the full-time science education program coordinator at University of Southeast and served as the academic adviser for all students in both the B.S. in Science Education program and M.A.T. with 9-12 Science Specialization program. To ensure that all participants had similar academic backgrounds, the researcher only recruited participants who were either junior or senior level undergraduates in the B.S. in Science Education program or in their first year of the M.A.T. with 9-12 Science Specialization program. Additionally, all recruits had completed General Chemistry I or the equivalent with a minimum final grade of “C-” or better. As the study focused specifically on the target population of pre-service science teachers, students who were currently or had previously been the teacher of record in a classroom were not included in the recruitment efforts.

Recruitment emails were sent to 19 science education majors at Southeast University who met the criteria described above. Fifteen students receiving the recruitment email volunteered for participation in the study. The final 12 participants were selected from the 15 volunteers based upon their availability to participate within the targeted two-week timeframe. All 12 participants exceeded the minimum recruitment requirement of completion of Chemistry I. All of the participants had completed two semesters of general chemistry by the time of the study. Additionally half of the participants had completed a semester of organic chemistry by the time of the study. The study was conducted during the summer so that potential participants were not currently enrolled in a course taught by the researcher and had completed their advisement and registration for the following fall semester during the prior spring semester.

Instrumentation

Pilot study instrumentation

Participants in the pilot study completed an eight-item questionnaire developed by the researcher (See Appendix A) during a regularly scheduled class meeting. The students were told their participation was voluntary. The participants were shown short videos of three different chemical phenomena: 1) solid lead (II) nitrate dissolving in distilled water; 2) solid potassium iodide dissolving in distilled water; and 3) the reaction of aqueous lead (II) nitrate and aqueous potassium iodide to form the precipitate lead (II) iodide. After each video, participants completed the relevant section of the questionnaire. For each dissolution video, there was a multiple choice item in which participants selected the best explanation of what happens as the solid is placed in the beaker. Based on chemical education research, the researcher developed four possible answer choices for the multiple choice item: a) it melts into the liquid phase; b) it separates into individual molecules; c) it separates into its component ions; d) it breaks apart into individual atoms. Participants were also asked to represent their understanding of the dissolution videos and the precipitation video by completing two open-ended items. The open-ended items included writing a chemical equation and drawing a picture of the phenomenon observed in the video assuming it was viewed through an extremely high powered scope. Participants were also provided a space to provide a written explanation of their drawings.

Study instrumentation.

Videos

Results from the pilot study were compiled and reviewed in order to determine if modifications were needed for the study. Analysis of the answers selected for the multiple choice items in the pilot study showed participants were inconsistent in explaining what happens as a solid is dissolved in water. After reviewing the data and the videos, the researcher suspected that the schlieren present in the dissolution of potassium iodide video may have influenced participants' answer choices. To mitigate any effects that the presence of schlieren in only one video may have had on participants, the researcher increased the number of videos shown. In this study, participants were shown a total of six videos ranging in length from one to three minutes each. The videos documented the following phenomena: 1) solid potassium iodide dissolving in distilled water; 2) solid lead (II) nitrate dissolving in distilled water; 3) the reaction of aqueous potassium iodide with aqueous lead (II) nitrate to produce the precipitate lead (II) iodide; 4) solid sodium hydroxide dissolving in distilled water; 5) solid iron (III) nitrate dissolving in distilled water; and 6) the reaction of aqueous sodium hydroxide with aqueous lead (II) nitrate to produce the precipitate iron (III) hydroxide. All of the dissolution videos had schlieren present, although in varying degrees.

In each of the dissolution videos, the appropriate mass of the ionic solid was dissolved in 250 milliliters of distilled water to produce a 0.01 molar solution. In the precipitation videos, appropriate volumes of the aqueous solutions were used based on the correct stoichiometric ratio to ensure formation of the precipitate. A magnetic stirrer was

used in each video. In the precipitation videos, the magnetic stirrer was turned off after the initial mixing of the reactants to facilitate the settling of the precipitate.

Questionnaire.

Results from the pilot study indicated that participants understood the multiple choice item and the two open-ended items. The same multiple choice item was used for each of the dissolution videos, with the only change being the name of the ionic solid. The study questionnaire included 16 items. The increase in items corresponded to the increase in the number of videos. For each of the four dissolution videos, participants were asked to answer the multiple choice item, write a chemical equation representing the phenomena, draw a picture of the phenomena, and provide a written explanation of the drawing and phenomena. For both of the precipitation videos, participants were asked to write a chemical equation, draw a picture of the phenomena, and provide a written explanation of the drawing and phenomena. For the complete questionnaire, see Appendix B.

Interviews.

Very few participants in the pilot study included written explanations of their drawings making it difficult for the researcher to interpret the drawings. Based on this, the researcher added individual interviews to this study. The purpose of the semi-structured interview was to allow participants an opportunity to verbally explain their drawings and to explain their thought processes for all items on the questionnaire. The interview also allowed the researcher to probe each participant's understanding of the processes of dissolution and precipitation. A set of questions was developed to guide each interview (See Appendix C).

The researcher interviewed each study participant after all videos were viewed and completion of the entire questionnaire. All interviews were video-taped using two cameras. One video camera was focused on the questionnaire in order to record anything participants may have pointed to during the interview. The second camera focused on the participants' torsos to record any hand gestures used during the explanations.

Data Collection

Each participant was scheduled for an individual hour and a half time slot to complete the data collection phase. Each participant was shown the six videos in the following order: 1) dissolution of solid potassium iodide; 2) dissolution of solid lead (II) nitrate; 3) precipitation of lead (II) iodide; 4) dissolution of sodium hydroxide; 5) dissolution of solid iron (III) nitrate; and 6) precipitation of iron (III) hydroxide. Immediately following each video, the participant was asked by the researcher to complete the items on the questionnaire related to that specific video. Participants were allowed to view the videos again if requested. After viewing all six videos and completion of the entire questionnaire, the researcher interviewed each participant using the answers and information provided by the participant on the questionnaire.

Data Analysis

Analysis of questionnaires.

The multiple choice items on the questionnaire were analyzed by the researcher to determine the frequency for which each answer choice was selected. As each multiple choice item was related to the chemical phenomenon of dissolving an ionic solid in water, it is expected that participants with a stable conception of this phenomenon would select the

same answer choice for each of the four multiple choice items. The frequency of the multiple choice answers were analyzed in two ways. First, the multiple choice answer frequencies for each individual participant were analyzed to determine if the participant held a stable conception of this phenomenon. The frequencies of the multiple choice answers for all participants were then analyzed to identify commonalities.

The chemical equations written by the participants on the questionnaire were analyzed by the researcher and identified by descriptive codes. The chemical equation codes were analyzed in two ways similar to the frequencies of the multiple choice questions. First the equation codes were analyzed for each participant to determine stability of their individual conceptions, and then they were further analyzed for all participants to identify commonalities in conceptions.

The drawings by the participants on the questionnaire were analyzed by the researcher and identified using descriptive codes. The drawing codes were analyzed similarly to the frequencies of the multiple choice questions and chemical equations. The drawings were first analyzed for each individual to determine the stability of the participant's conceptions and representations. The drawings were further analyzed across all participants to identify commonalities in conceptions and representations.

Analysis of interviews.

The videotapes of the interviews were transcribed and analyzed by the researcher. For each chemical phenomena, the corresponding questions of the interview were analyzed to identify conceptions held by the participants. All conceptions were identified including conceptions considered conceptually correct, as well as, alternative conceptions. Each

identified conception was given a code, consisting of a descriptive name or phrase. When applicable, descriptions identified in previously published research were used. A second researcher with a background in chemical education analyzed the transcripts using the coding system developed by the researcher. All differences in coding were discussed by the two researchers until agreement was reached on the appropriate code.

After all transcripts were coded, the researcher analyzed the codes in two ways. First, the transcripts for each participant were analyzed to determine the consistency of conceptions held by each individual participant. The transcripts were further analyzed to identify common conceptions held by multiple participants. After analyzing the transcripts, the researcher analyzed the data from the multiple choice answers, the chemical equations, the drawings, and the interviews for each individual participant to determine if participants held a stable conception between the various representations of the same chemical phenomena.

Limitations

While the results of this study have hopefully provided information to better understand pre-service science teachers' mental models of dissolution and precipitation reactions, there are several limitations. First and foremost the sample size of 12, while a reasonable number for a qualitative study involving individual interviews, is too small to allow the results to be generalized to larger populations. Additionally, the participants for this study were selected using a combination of purposive and convenience sampling techniques, which further limit the ability to generalize the results. The researcher does not attempt to conclude that the results of this study are representative of all pre-service secondary science teachers.

CHAPTER 4
RESULTS

This study was conducted to identify the mental models held by pre-service secondary science teachers about the chemical processes of dissolution and precipitation reactions.

The Study Subjects

Nineteen pre-service secondary science teachers were invited to participate in the study based upon their successful (a final grade of C or higher) completion of one semester of introductory general chemistry consisting of both lecture and laboratory components. From the 19 invitations, 15 pre-service secondary science teachers agreed to participate in the study. Twelve participants were selected from the 15 respondents solely based upon their availability to participate within the prescribed timeframe of the study. Pre-service science teachers at University of Southeast complete one of four areas of scientific concentration as part of the degree requirements. The number of courses required in the four science disciplines – biology, chemistry, geology, and physics is dictated by the science concentration. Table 4.1 shows the number of participants in each science concentration.

Table 4.1 Number of Participants by Area of Science Concentration

<i>Concentration Area</i>	<i>Number of Participants</i>
Biology	10
Chemistry	1
Earth Science	0
Physics	1

Although the participants varied in their area of scientific concentration, each concentration requires completion of at least three semesters (12 semester hours) of chemistry coursework. The three required chemistry courses are General Chemistry I, General Chemistry II, and Organic Chemistry I. The topics of dissolution and precipitation are introduced in General Chemistry I. Table 4.2 provides data on the chemistry background of the study participants.

Table 4.2 Amount of Chemistry Semester Hours Completed by Participants

<i>Number of Chemistry Semester Hours Completed</i>	<i>Number of Participants</i>
4	0
8	6
12	5
More than 12	1

Note. Participation in the study required a minimum of 4 semester hours in chemistry.

As shown in Table 4.2, all of the study participants exceeded the minimum requirement of completing one semester (4 semester hours) of chemistry. One half of the participants had completed two semesters (8 semester hours) of chemistry, while five had completed three semesters (12 semester hours) of chemistry. The sole participant who completed the chemistry concentration had significantly more instruction in chemistry than the other participants.

Dissolution of Ionic Solids Data Analysis

Participants were shown four videos of ionic solids dissolving in water: potassium iodide, lead (II) nitrate, sodium hydroxide, and iron (III) nitrate. Following each video, participants answered a multiple choice question in which they were asked to select the answer choice that best matched their idea of what happened when the ionic solid was placed in a beaker of water. Participants were then asked to write a chemical equation that represented the observed phenomenon. Participants were also asked to draw an image of the observed phenomenon imagining that it was being viewed under an extremely powerful scope that allowed the components to be seen separately. The word component, rather than ions or particles, was used to potentially reduce any influence on participants' responses. Participants were asked to provide a written explanation of their drawings. The researcher interviewed the participants about their answers and responses to seek additional clarification of the participants' understanding of the phenomenon at hand.

The data from the multiple choice items were analyzed to determine the frequency of responses for each answer choice. Several participants initially selected a multiple choice answer, but later asked to change the response after providing a written explanation of their drawing or after providing verbal explanations during the follow-up interview. The frequency of each initial response was also recorded to provide insight into the mental models of the participants.

The data from the participant produced equations and drawings were treated as qualitative data. All of the participants' equations and drawings were reviewed by the researcher and phrases were developed to describe the equations and drawings. All of the

descriptive phrases were listed and then grouped into thematic categories. The interview data was analyzed similarly to the equations and drawings data. Interview transcripts were coded with descriptive phrases, which were later grouped into thematic categories.

Data for the dissolution of each of the four ionic solids follows. After the data for all of the solids are presented, an analysis of consistency of responses by individual participants is provided.

Dissolution of Potassium Iodide

For the first dissolution video, two-thirds of the participants selected an answer for the multiple choice question and changed the response after providing written explanations of the accompanying drawing or oral explanations during the interview. Table 4.3 shows the frequency of initial responses that were later changed by the participants. Participants changed their responses while completing the questionnaire or in some cases during the subsequent interview. One half of the participants initially selected the misconception that solid potassium iodide melts into the liquid phase when placed in a beaker of water as their answer choice.

Table 4.3 Initial Multiple Choice Responses for Dissolution of Potassium Iodide

<i>Multiple Choice Response</i>	<i>Number of Responses Initially Selected</i>
It melts into the liquid phase	6
It separates into the individual molecules	1
It separates into its component ions	0
It breaks apart into individual atoms	1

Note. The number of responses in this table does not total 12, since some participants did not change their initial answer choice.

Participants' reasoning for selecting an answer and then changing it were varied. The most common reason for selecting an answer and later changing it dealt with participants focusing on macroscopic or observable characteristics of the phenomenon. Below are excerpts from a few of the interviews in which participants explain the reason for selecting an answer initially and why the response was changed. (R stands for researcher and P# identifies the participant by number.)

- R: Okay, now I happened to notice as you were doing this you initially selected A.
- P1: Right.
- R: And then you went back and changed it. Could you tell me what was your thinking when you thought A and then what prompted you to change the answer?
- P1: When I went with A, the video looked like it just melted, but then, I had to actually throw some scientific thought to it, and so I didn't think it was that.
- R: If we go back to that video would you point and kind of indicate to me what about the video you said it looked like it was melting. Would you indicate to me what that is? (*Replays video*)
- P1: It kind of just looks like it's melting here (*pointing to video*) cause it looks like its kind of ice-like crystalline kind of structure.

In this exchange, Jane (P1) pointed to the video where she thought it looked like the solid appeared to be melting like ice. See Figure 4.1 for the screen capture of the video to which Jane pointed.

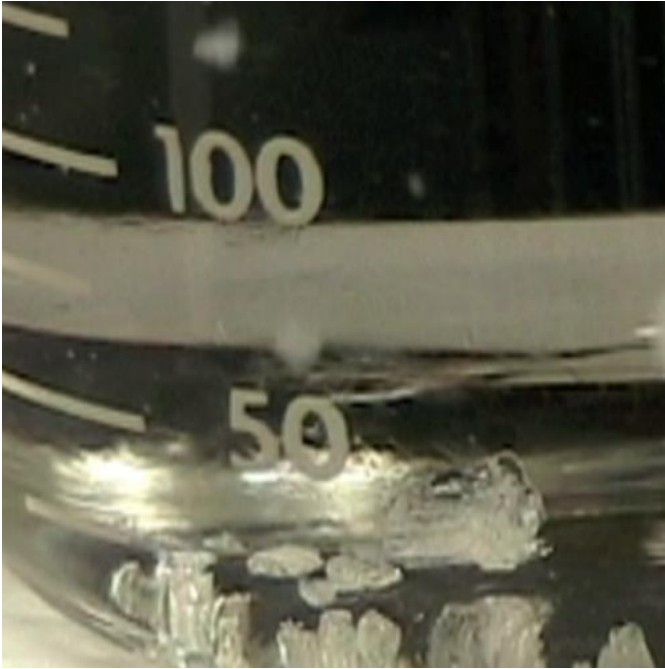


Figure 4.1 Screen Capture of Potassium Iodide Dissolution Video

Below is Samantha's (P3) reason for initially selecting melting based upon the misconception that the solid disappears:

- R: What was your thinking when you originally thought it was melting?
P3: Umm, I guess when I saw it like it, it just completely disappeared ...my instinct was it's just liquid so then obviously there's more choices so I had to think about which one would be possible.

A couple of participants believe that the dissolution of an ionic solid in water is a two step process. When interviewed about their multiple choice answer, these participants

explained their reasoning and indicated that there were two correct answers to the multiple choice question. An excerpt of Melissa's (P10) interview illustrates this point:

- R: Okay. In item #1 I noticed that you chose dissolved potassium iodide (A) melted into the liquid phase. Could you explain your reasoning for selecting that answer?
- P10: Um, I just figured that any solid mixed with heat just automatically has to melt. The molecules have to break apart as well.
- R: So it has to...
- P10: I see it as being a mixture of the molecules breaking down and then it becomes liquid phase.
- R: So you think it is both (B) and (A).
- P10: Yeah

Jasmine (P9) differed from the other participants. Throughout her interview, she attempted to reconcile her understanding of the observed phenomenon and her representations of that phenomenon. The excerpt below is an example of how Jasmine initially selected an incorrect answer to the multiple choice question, but ultimately decided on another answer after thinking about the equation and drawing she had provided.

- R: Okay. We will start with #1. I would like for you to explain to me with the potassium iodide you chose (A) that it melts into the liquid phase. Can you talk to me about how you got that answer?
- P9: I chose that it melts into the liquid phase because I thought it dissolved into it because it was not visible anymore. Now that I think about it, it just broke down to smaller molecules. For my equation, it is just broken down. .. (*pauses and looks at equation*)
- R: You can change your answer if you want to. So if you will keep talking to me.
- P9: Okay.
- R: So you thought originally that it was (A).
- P9: Originally I thought it was (A) because it was not visible anymore in the liquid so I chose (A) it melts into liquid phase. Then I realized like in the equation it still separated although the visible eye cannot see it. Because it is not together. It didn't become one compound.
- R: Okay. So what do you think, what would you choose now for answer 1, for the answer?
- P9: Um...

- R: Do you want to keep (A) as the answer or do you want to choose one of the other choices?
- P9: I will go with (C) it breaks into its component ions.

Table 4.4 shows the frequency of final responses to the multiple choice question about the dissolution of solid potassium iodide. While half of the participants ultimately selected the correct answer that solid potassium iodide would separate into its component ions after being placed in a beaker of water, one quarter of the participants selected the misconception that the solid potassium iodide melts into the liquid phase. The remaining participants understood that solid potassium iodide separates or breaks apart, but did not select the appropriate terminology for the components of an ionic solid.

Table 4.4 Final Multiple Choice Responses for Dissolution of Potassium Iodide

<i>Multiple Choice Response</i>	<i>Number of Responses</i>
It melts into the liquid phase	3
It separates into the individual molecules	2
It separates into its component ions	6
It breaks apart into individual atoms	1

Participants were asked to write an equation representing the phenomenon of solid potassium iodide being placed in a beaker of water. The resulting equations were sorted into five thematic categories: 1) change in state, 2) creation of new compounds through combination of the solid and water, 3) separation of water into components, 4) separation of solid into incorrect or partially correct components, and 5) separation of solid into correct

components with correct charges. Table 4.5 includes the number of responses in each category along with examples of participants' equations. Examples of each category of responses are illustrated in the following interview excerpts.

Susan (P2) consistently explained her equation (Figure 4.2) and reasoning based on her mental model in which dissolving and melting are the same thing, and melting means the solid becomes part of the water.



Figure 4. 2 Susan's Dissolution of Potassium Iodide Equation

- R: Okay, okay, so how did you come about your equation for number 2?
- P2: I guess because the actual solid was no longer there. I assumed it became part of the water.
- R: Okay, so talk to me about what the terms melting and dissolving mean to you. What does it mean to you to say something melts?
- P2: I guess when I think of something melting I just think of it probably getting hot and it, it melts I guess (*laughs*), umm, it gets hot and maybe it changes forms, you know. If it's melting it means it was in one state and when it melts it's in another state, kind of like with ice, you know what I mean, When it gets hot, it once was a solid, when it gets hot it becomes a liquid. I guess that's what I think of when I think of melting. You know when there's snow, when it first falls, there's the snow and as the sun comes out it becomes a liquid and it melts. I guess that's what I think of.
- R: Okay, so what about the term dissolving? What does that mean to you?
- P2: I guess it for me might would be the same thing, I look at it as maybe being in one form and when it dissolves it becomes something else. Kinda to me, I think melting and dissolving would be the same thing.

Ben's (P5) equation (Figure 4.3) and interview excerpt is an example of two categories: creation of new compounds through the combination of the solid and water and separation of water into components. One half of the participants' equations were coded as these two categories.

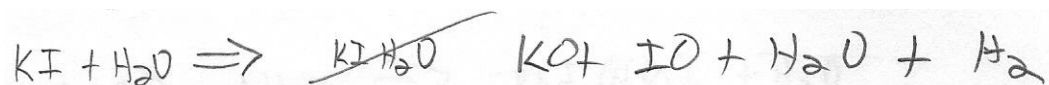


Figure 4. 3 Ben's Dissolution of Potassium Iodide Equation

- R: Okay. Alright, so, with #2 your equation that you have there, could you explain to me your reasoning for how you came up with that equation?
- P5: Umm, well I knew there were two compounds available. There was the potassium iodide going into the water medium. So you combined the two. I know that's not correct. Umm, that is kind of what I had. It was no longer going to be potassium iodide and water. They were going to be different bonds and different compounds.
- R: Okay. Are you saying that that is one compound that is formed?
- P5: No. I can't remember my chemistry. Umm, I am sure that there are several, still going to be separate water in there and probably it would be more accurate to say that the potassium plus iodide plus H₂O. Actually, the H₂O to a degree would have probably been, some of the H₂O molecules would have had to have been broken. It would have combined with the potassium iodide to form totally different compounds.
- R: So if that is what you think do you want to change, to write, what you think may have happened. You can just do like a line and then write what you just said.
- P5: Well, it may be but this is not going to be accurate either because it would be something like potassium oxide plus iodine oxide. That is going to mean that you are going to have broken up some of the H₂O so there probably would be something like an H₂, something like that would be a little bit more reasonable.

Three participants' equations were categorized as separation of the solid into incorrect or partially correct components. Amanda's (P4) equation (Figure 4.4) and interview excerpt is an example of this category as she does not represent the components as ions. It also illustrates an unclear understanding of particle level terminology:



Figure 4. 4 Amanda's Dissolution of Potassium Iodide Equation

- R: Umm, then with number two, can you kind of explain to me how you came up with your equation here? Just the process again of how you came up with that.

- P4: Well, when I chose my answer for number one the individual molecules so I did the same here, that's kind of individual atoms except for the H₂O – that's a molecule, so that's why I really just had it between B and D after all of them ...so it's broken down
- R: Okay, umm, this is kind of related back to what you just said for number two but also number one, you were saying that B, C, and D are very similar, umm, pretty much the difference is that one is molecules, one is ions, and one is atoms, do those terms mean different things to you?
- P4: Uhh, yeah like molecules would be the H₂O or the KI, the potassium iodide would be a molecule, right,
- R: Okay, those are examples could you maybe in your own words try to explain like the definition of what a molecule is...
- P4: A molecule is like when two atoms are joined together
- R: Okay, okay and so then what would ions be
- P4: Two charged ...(*pauses*)
- R: Two charged?
- P4: particles, ions that are charged molecules I guess, charged atoms joined together
- R: Okay, and then what would atoms be?
- P4: The single form of the element

Two of the participants provided equations that are accurate and were categorized as separation of the solid into correct components with correct charges. Kim's (P7) equation (Figure 4.5) and interview excerpt is below:

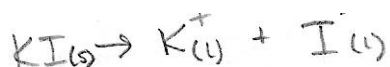


Figure 4. 5 Kim's Dissolution of Potassium Iodide Equation

- R: Okay. For #2 would you like to explain to me how you came up with that equation?
- P7: I just broke it down to its positive and negative ions.

Although William's (P12) equation (Figure 4.6) is accurate, his explanation illustrates incorrect use of terminology:



Figure 4. 6 William's Dissolution of Potassium Iodide Equation

- R: Okay, if you could talk through your equation for #2? How did you come up with that equation?
- P12: It seemed pretty straightforward. You have your solid potassium iodide. Since they are just breaking apart into their component atoms, I would break them down into component atoms. Remembering, just double checking each one's respective charges, potassium having a +1 charge and iodide having a negative charge.

Table 4.5 Thematic Categories of Participants' Equations Representing Dissolution of Potassium Iodide

<i>Thematic Category</i>	<i>Number of Responses</i>	<i>Examples</i>
Change in state	1	$KI \rightarrow H_2O$
Creation of new compounds through combination of solid and water	7	$KI(s) + H_2O(l) \rightarrow HI(l) + KOH(l)$ $KI + H_2O \rightarrow KH_2O$
Separation of water into components	6	$KI + H_2O \rightarrow KOH + IH$ $I + H$ Final $K\overset{\ominus}{I} + H_2O \xrightarrow{\overset{\oplus}{O-H}} KI + OH$
Separation of solid into incorrect or partially correct components	3	$KI \xrightarrow{H_2O} K + I + H_2O$ $KI^+ + H_2O \rightarrow K^+ + I_2 + O_2 + H^+$
Separation of solid into correct components with correct charges	2	$KI \rightarrow K^+ + I^-$

Note. The number of responses does not total 12 since the responses could be placed in multiple categories.

Participants were asked to draw an image representing the phenomenon of solid potassium iodide being placed in a beaker of water if it were viewed with an extremely powerful scope that would allow the viewer to see each component separately. Space was provided on the questionnaire for participants to provide a written explanation of their drawings. The pictures were sorted into six thematic categories. The first five thematic categories were the same as those used for the equations: 1) change in state, 2) creation of new compounds through combination of the solid and water, 3) separation of water into components, 4) separation of solid into incorrect or partially correct components, and 5) separation of solid into correct components with correct charges. A sixth category was added for the drawings: macroscopic representations for drawings in which participants represented macroscopic observations. Table 4.6 includes the number of responses in each category.

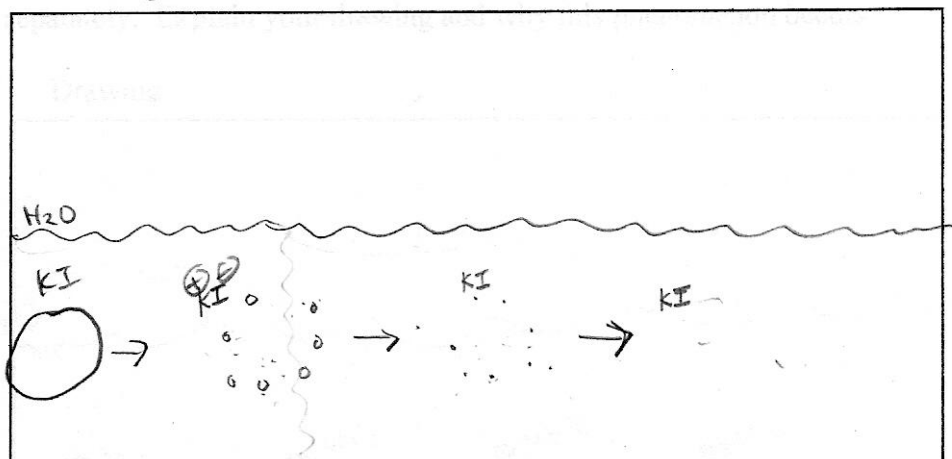
Table 4.6 Thematic Categories of Participants' Drawings of the Dissolution of Potassium Iodide

<i>Thematic Category</i>	<i>Number of Responses</i>
Change in state	3
Creation of new compounds through combination of solid and water	4
Separation of water into components	4
Separation of solid into incorrect or partially correct components	3
Separation of solid into correct components with correct charges	3
Macroscopic representation	2

Note. The number of responses does not total 12 since the responses could be placed in multiple categories.

Examples of the six categories of drawings are illustrated in the following interview excerpts. Melissa's (P10) drawing (Figure 4.7) and explanation is an example of the change in state category. Melissa is one of the participants who selected two answer choices for the multiple choice item. She explains how the solid both melts and separates.

Drawing



Explanation: It continues to melt until it disappears

Figure 4. 7 Melissa's Dissolution of Potassium Iodide Drawing

- P10: This line (*pointing to line in drawing*) is the H₂O. Then each one of these individual pictures is the potassium iodide. It started off as bulky molecules and then it just digressed until it disappeared into nothing. It became one liquid.
- R: Okay. So does this whole circle represent KI or does...
- P10: Each individual spot represents a molecule of KI.
- R: Okay. So this would be like 1, 2, 3, 4, 5, 6, 7 different molecules of KI and those molecules are just getting smaller is what you are representing?
- P10: Yes.
- R: Okay. So talk to me about...up at #1 you said that it is really a combination of (B) and (A) that it is separating going into the liquid phase. How does that apply to your drawing here?
- P10: Um, these are individual molecules. And they just...they started off like altogether as one big KI component.
- R: Okay.
- P10: Then it became into their separate molecules. Then their molecules just went into the liquid phase until it went into nothing.
- R: Okay. Could you try to tell me what you think those separate molecules are? That you said this one big molecule and it becomes separate molecules.
- P10: Um.
- R: What would those separate molecules be?
- P10: The atoms.

- R: So what would those be? If you had to identify them, what type of atoms are they?
- P10: Um, ohh, ionic atoms. Is that what you are asking me or something?
- R: Um, like um what elements do you think they are when you are saying they're atoms?
- P10: K is positive and this (*points to I in KI listed in item #1*) is negative so it is an ionic bond.
- R: That is part of it. I guess what I am asking here is you are saying that here they are one molecule and then you said they separate into their separate. So what would those separate?
- P10: Um, I guess this would be positive and this would be negative so it would separate into potassium and iodine.

As seen in the previous interview excerpt, Melissa (P10) explained the chemical phenomenon as melting because it disappeared. In her mental model, a substance that melts is viewed as one in which the components continually get smaller and smaller until they are no longer visible. Melissa's understanding is based upon her macroscopic observations of the solid disappearing, which to her means it is melting. However, she does incorporate her previous ideas in which dissolution is viewed as a two step process. Melissa thinks that the potassium iodide initially breaks down into "molecules/ionic atoms". Once separated into "molecules/ionic atoms", those components "go into the liquid phase until they become nothing." Melissa's drawing was categorized as both change in state and macroscopic representation. Her verbal explanation of the drawing during the interview resulted in her response also being included in a third category: separation of solid into the correct components with the correct charges.

Susan's (P2) drawing (Figure 4.8) and explanation illustrate a unique mental model of dissolving and melting. As seen in an earlier interview excerpt, Susan thinks that dissolving and melting are the same thing. While several of the other participants have this

Later in the interview,

- R: Okay is that how it would start, how it would end, would it change at all? What do you think? So imagine if you like watched that whole video with that powerful scope.
- P2: Okay, if I watched the whole video then this probably would be the beginning (*pointing to linear structure on questionnaire*), but by the time you got to the end, umm, you might couldn't see the particles anymore...you might just would see the ...I don't know...maybe, okay well then if you saw it in a in a under the microscope you might would see those particles look like this , but as they dissolved in water they might become something else...some other kind of particle...maybe smaller and a lot more.
- R: Okay, could you try to draw what you think it might look like at the end?
- P2: Okay, well then maybe...
- R: And if you don't mind, would you write beginning beside that drawing (*pointing to previous drawing on questionnaire*). So that's what you're saying it would look like at the beginning.
- P2: And at the end it might would be a bunch of little molecules together (*drawing on questionnaire*)
- R: And what do you think those molecules might be? You know here (*pointing to beginning drawing*) you said that might be a K and that might be an I.
- P2: These here (*pointing to drawing*) ...that might be the same molecule, but because they've been...no, they wouldn't be the same because they melted. Maybe this would just be the water.
- R: Okay, if you'll just label what you think it might be.
- P2: Okay, I'm just going to say these are the water molecules here (*labels on drawing*) – okay.
- R: And that's, that's what you think is at the middle, the end?
- P2: All of them around...I think this is the end.
- R: Okay, and so what do you think happened from the beginning to the end? You're saying it's gone from KI to water
- P2: Because it melted, because these here melted, then they're all just, because they melted in the beaker of water I guess I'm just thinking that now everything is a liquid, so everything would be water, which probably wouldn't be right, but I guess I just think of it being melted, it just being gone, so now it's transformed into something else because it was in the water then it just is part of the water
- R: Okay so you're saying this (*points to beginning drawing*) transformed into this (*points to end drawing*)? And again, this is to make sure I interpret what you're saying correctly.
- P2: Umm, maybe...I guess...what I think of it as melting , maybe it dissolves but it actually doesn't go away ...it's the same thing but the form is just changed, so maybe this is water and this here in another form

Through continued questioning during the interview, Susan gradually moved from her initial illustration that focused solely on macroscopic properties (the volume of liquid increases in the beaker) to her unique representation of the dissolution of an ionic solid. For all four of the ionic solids, Susan illustrated her model of dissolving as one in which the solid has changed forms into a ring of alternating solid particles and water molecules, which are both in the liquid state.

Jane's (P1) drawing (Figure 4.9) and interview excerpt is an example of the categories creation of new compounds through the combination of the solid and water and separation of water into components.

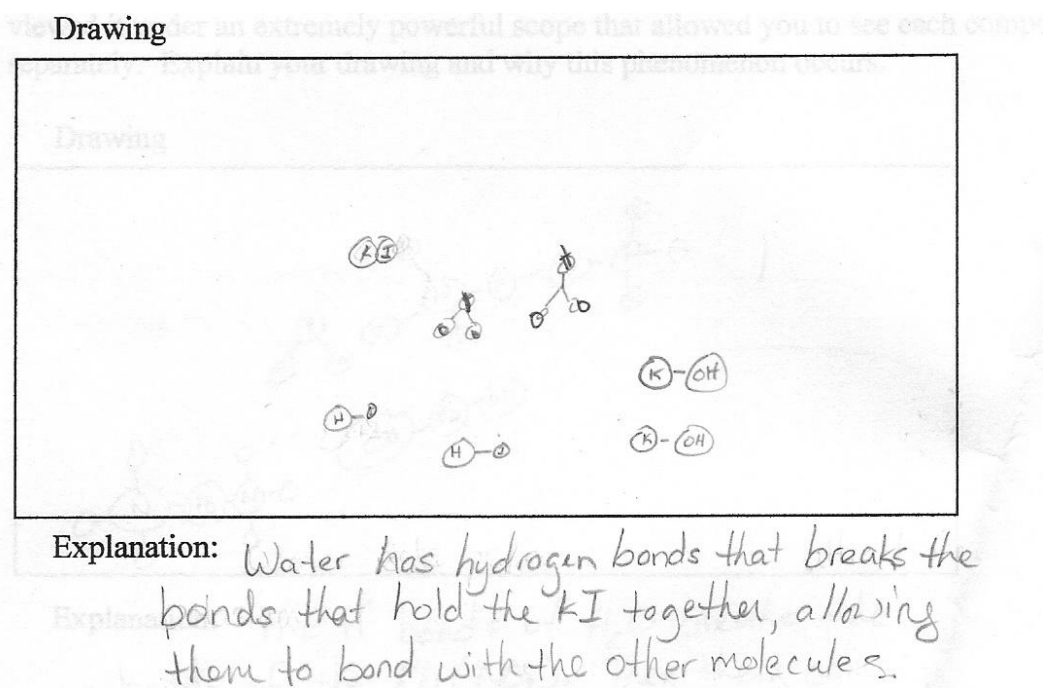


Figure 4. 9 Jane's Dissolution of Potassium Iodide Drawing

P1: Pretty much I show where you have some water molecules here, you have your ionic acids here, umm this is your original potassium iodide. They come

together, their bonds break and they come back together to form your potassium hydroxide and your ionic acid.

R: Okay, to help me remember

P1: Umm, excuse me, that's iodide, what is that hydrogen that seems like an iodide ...is it?

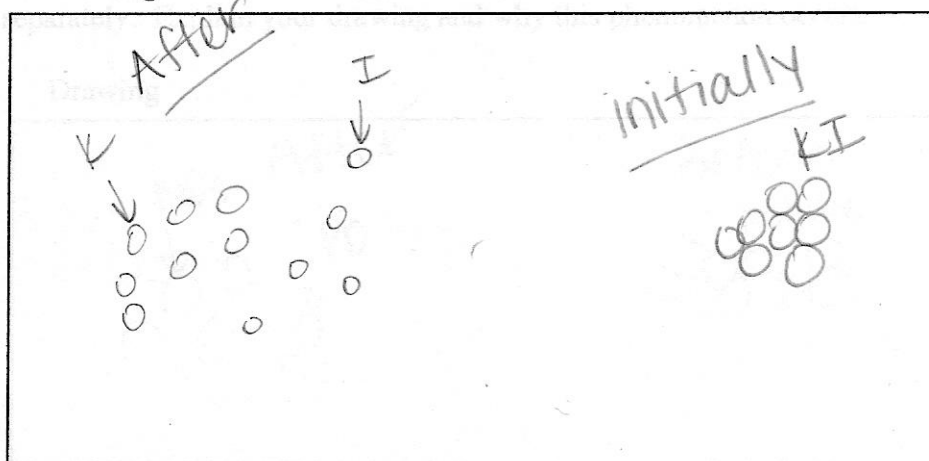
R: Okay you pointed to two and called them water, would you just maybe draw an arrow to those just in case I couldn't

P1: Okay (*labels water molecules*), H and two O's, H and O.

Jane's excerpt and diagram illustrate a common misconception seen throughout the interviews in which dissolution is viewed as a type of chemical reaction in which the solid breaks down and then bonds with either the water or components of the water to form entirely new compounds.

Three participants' drawings were categorized as separation of solid into incorrect or partially correct components. In each of these cases, the participants recognized potassium iodide breaks down, but did not include charges or had incorrect charges in their drawings. Samantha's (P3) drawing (Figure 4.10) and excerpt are an example of this category:

Drawing for an extremely powerful scope that allowed you to see each component



Explanation:

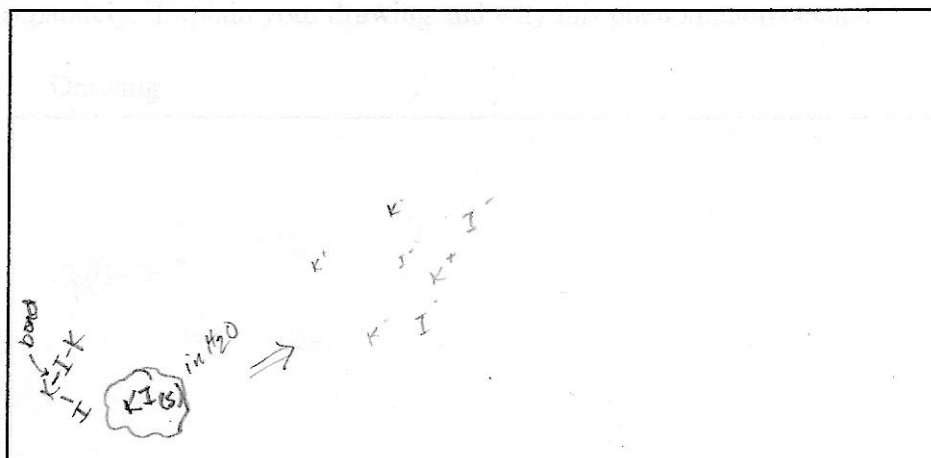
In the beaker the KI dissociates into separate molecules of K and I

Figure 4. 10 Samantha's Dissolution of Potassium Iodide Drawing

- P3: Okay, these are (*pointing to circles on left of drawing*) just the individual molecules of the potassium and the iodide
- R: So is that...
- P3: So this is after
- R: After, what do you think it looks like initially?
- P3: They're all together.
- R: Could you try to draw that for me?
- P3: Yeah (*draws initial representation on right side of box and labels initially*), so they would be one big compound.

Three participant's drawings were categorized as separation of solid into correct components with correct charges. Kim's (P7) drawing (Figure 4.11) and excerpt is representative of this category:

Drawing



Explanation:

KI(s) dissolves into its constituent ions in the H_2O creating a solution. The K^+ + I^- ions are in solution.

Figure 4. 11 Kim's Dissolution of Potassium Iodide Drawing

- R: Alright. For your drawing here, if you will talk to me about what this means here. I am assuming is this like what would be the start of the video (*pointing to circle labeled KI*).
- P7: Yes. That is the start of the video. Put in the water. It breaks up into its constituent ions there (*points to left side of drawing*).
- R: Okay.
- P7: Ks and Is
- R: Okay. Could you maybe just draw or sketch real quickly for me what do you think that potassium iodide would look like before it went into the water? If you were looking through that very powerful scope, what would it look like?
- P7: It would like little Ks and Is bonded together.
- R: What would that...just try to quickly represent what you think it might look like?
- P7: (*Sketches K-I*) That would just represent a bond I guess. (*continues sketching K-I*) a K and I, so on and so forth.

Dissolution of Lead (II) Nitrate

As mentioned earlier, numerous participants selected an answer for the multiple choice question and changed the response. Table 4.7 shows the frequency of initial responses regarding the dissolution of lead (II) nitrate that were later changed by the participants. There was a decrease in the number of participants changing their answer from the first dissolution video to the second video.

Table 4.7 Initial Multiple Choice Responses for Dissolution of Lead (II) Nitrate

<i>Multiple Choice Response</i>	<i>Number of Responses Initially Selected</i>
It melts into the liquid phase	1
It separates into the individual molecules	0
It separates into its component ions	0
It breaks apart into individual atoms	1

Note. The number of responses in this table does not total 12, since some participants did not change their initial answer choice.

As was seen with the dissolution of potassium iodide, participants had a variety of reasons for changing their initial answer. William (P12) explained in his interview his process for selecting the answer. William initially selected the correct answer choice for three of the four ionic solids. This excerpt illustrates how William initially reverted back to macroscopic observations when he forgot his solubility rules

R: Okay. So let's look at the next page. For this one for the lead II nitrate you actually circled (A) that it melts into the liquid phase. Could you explain your reasoning for that?

- P12: Um, just by first appearance I thought it wasn't dissolving, that it was just breaking apart due to the motion of the...I don't even remember the correct term for the white...
- R: Stir bar
- P12: Stir bar
- R: Was there anything else in there that made it look like it was melting? Was there something in the video?
- P12: I thought it was, at this point it came down to a process of elimination through the multiple choice. Then I realized afterwards that I forgot my solubility rules.
- R: Okay.
- P12: It comes down to I just forgot my solubility rules. I realized that lead nitrate will break apart into lead and NO_3 . I simply forgot my solubility rules.

As previously seen in Melissa's responses to the dissolution of potassium iodide, Samantha (P3) also thinks the dissolution of ionic solids in water is a two step process. An excerpt of her interview illustrates this point:

- R: Okay, all right let's look at the second one here, would you try to explain or explain to me what your process is with coming up with A and C for number 4?
- P3: A and C, okay, well same reasoning pretty much as the first one, it turns into a liquid.
- R: Umhuh
- P3: And then the umm ions I just assumed that they can be broken up into just the NO_3 and the lead.

Table 4.8 shows the frequency of final responses to the multiple choice question regarding the dissolution of solid lead (II) nitrate. While one half of the participants ultimately selected the correct answer that solid lead (II) nitrate would separate into its component ions after being placed in a beaker of water, 42% of the participants chose the misconception that the solid lead (II) nitrate melts into the liquid phase.

Table 4.8 Final Multiple Choice Responses for Dissolution of Lead (II) Nitrate

<i>Multiple Choice Response</i>	<i>Number of Responses</i>
It melts into the liquid phase	5
It separates into the individual molecules	2
It separates into its component ions	6
It breaks apart into individual atoms	0

Note: The number of responses does not total 12 since one participant selected multiple answers.

Participants' equations for representing the dissolution of lead (II) nitrate were sorted into the same five thematic categories used in the dissolution of potassium iodide: 1) change in state, 2) creation of new compounds through combination of the solid and water, 3) separation of water into components, 4) separation of solid into incorrect or partially correct components, and 5) separation of solid into correct components with correct charges. Table 4.9 includes the number of responses in each category along with examples of student's equations. Examples of each category are illustrated in the following equations and interview excerpts.

Susan's (P2) equation (Figure 4.12) and explanation continue to provide evidence of her mental model in which dissolving is the same thing as melting. The only difference seen in Susan's response to this video, is her equation now reflects the idea that the substance stays the same and only changed states.

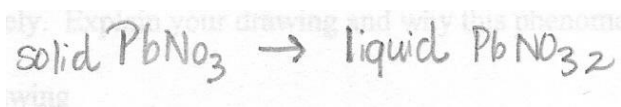


Figure 4. 12 Susan's Dissolution of Lead (II) Nitrate Equation

- R: Okay, all right, so how did you get this chemical equation?
 P2: I just said it went from a solid to a liquid.

Jasmine's (P9) equation (Figure 4.13) and interview excerpt is an example of two categories: creation of new compounds through the combination of the solid and water and separation of water into components. Almost one half of the participants' equations were coded as these two categories.

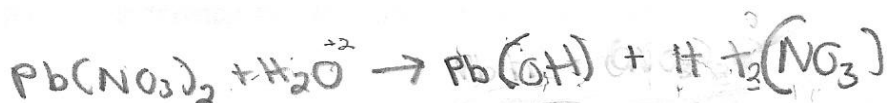


Figure 4. 13 Jasmine's Dissolution of Lead (II) Nitrate Equation

- P9: What I was thinking was, I was just putting lead with hydroxide. I know that there is another hydrogen there so I put like that would escape into the air. I know you can't separate nitrates. So I just left it alone here. I know it is supposed to be balanced. I am supposed to use the chemical, the periodic table to balance it. But I didn't so.
 R: That's okay.
 P9: So I know that the compound is going to form a new compound and some is going to be released into the air. So that is why I put that it is separating into different molecules.

Five participants' equations were categorized as separation of the solid into incorrect or partially correct components. Amanda's (P4) equation (Figure 4. 14) and interview excerpt is an example of the uncertainty participants had regarding the behavior of polyatomic ions in water and the common mistake in which components were not written as charged ions:

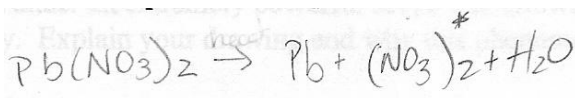


Figure 4. 14 Amanda's Dissolution of Lead (II) Nitrate Equation

- P4: Well first of all I had no idea, so I just broke this (*pointing to $Pb(NO_3)_2$ in equation*) up, but I think you're supposed to do something with the NO_3 too, I think you're supposed to break that down further but I, I just couldn't remember how to get that, but I just broke them up into molecules and then single atoms.
- R: Okay, does the little asterisk here (*pointing to equation*) mean anything in particular?
- P4: Yeah, because I knew something else had to be done to that, but I just wasn't sure.

William (P12) was the sole participant who provided an accurate equation for the dissolution of lead (II) nitrate and was categorized as separation of the solid into correct components with correct charges. William initially thought the solid melted, but during the interview realized that was incorrect. As a result of his changing his multiple choice answer, William corrected his equation (Figure 4.15) to reflect his mental model of the process. An excerpt from his interview follows:

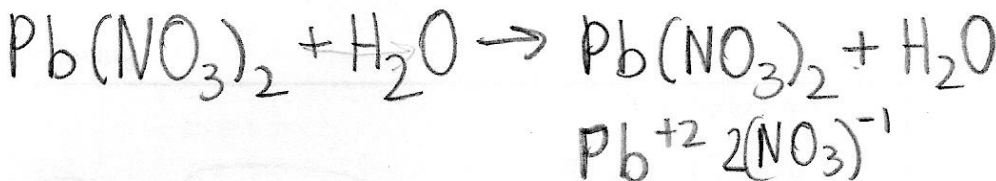


Figure 4. 15 William's Dissolution of Lead (II) Nitrate Equation

- P12: The new equation would be lead nitrate, they would break apart into their individual components because lead II nitrate is soluble. They would break apart very similar to the last equation as an example. They would have their respective charges. In this case, lead II would tell me that lead would have a +2 charge (*writes Pb^{+2} on equation*). NO_3 would have a -1 charge (*writes NO_3^- on equation*). To balance out your ionic formula, trying to remember my proper terminology you would have to remember there are two NO_3 s.

Table 4.9 Thematic Categories of Participants' Equations Representing Dissolution of Lead II Nitrate

<i>Thematic Category</i>	<i>Number of Responses</i>	<i>Examples</i>
Change in state	1	$\text{solid PbNO}_3 \rightarrow \text{liquid PbNO}_3$
Creation of new compounds through combination of solid and water	4	$\text{Pb(NO}_3)_2 + \text{H}_2\text{O} \rightarrow \text{Pb(NO)}_2\text{H}_2\text{O}$ $\text{Pb(NO}_3)_2 + \text{H}_2\text{O}^{+2} \rightarrow \text{Pb(OH)} + \text{H}^+ \text{ } \frac{1}{2}(\text{NO}_3)$
Separation of water into components	5	$\text{Pb(NO}_3)_2 + \text{H}_2\text{O} \rightarrow 2\text{Pb}^+ + 2\text{NO}_3 + \text{O}_2 + \text{H}^+$ $\text{Pb(NO}_3)_2 + \text{H}_2\text{O}^{+2} \rightarrow \text{Pb(OH)} + \text{H}^+ \text{ } \frac{1}{2}(\text{NO}_3)$
Separation of solid into incorrect or partially correct components	5	$\text{Pb(NO}_3)_2 \rightarrow \text{Pb} + (\text{NO}_3)_2 + \text{H}_2\text{O}$
Separation of solid into correct components with correct charges	1	$\text{Pb(NO}_3)_2 + \text{H}_2\text{O} \rightarrow \text{Pb(NO}_3)_2 + \text{H}_2\text{O}$ $\text{Pb}^{+2} \text{ } 2(\text{NO}_3)^{-1}$

Note. The number of responses does not total 12 since the responses could be placed in multiple categories

Participants drew an image representing the phenomenon of solid lead (II) nitrate being placed in a beaker of water as if it were viewed with an extremely powerful scope that would allow the viewer to see each component separately. The pictures were sorted into the same six thematic categories as used with the dissolution of potassium iodide drawings: 1) change in state, 2) creation of new compounds through combination of the solid and water, 3) separation of water into components, 4) separation of solid into incorrect or partially correct components, 5) separation of solid into correct components with correct charges, and 6) macroscopic representations. Table 4.10 includes the number of responses in each category. Examples of the six categories of drawings are illustrated in the following interview excerpts.

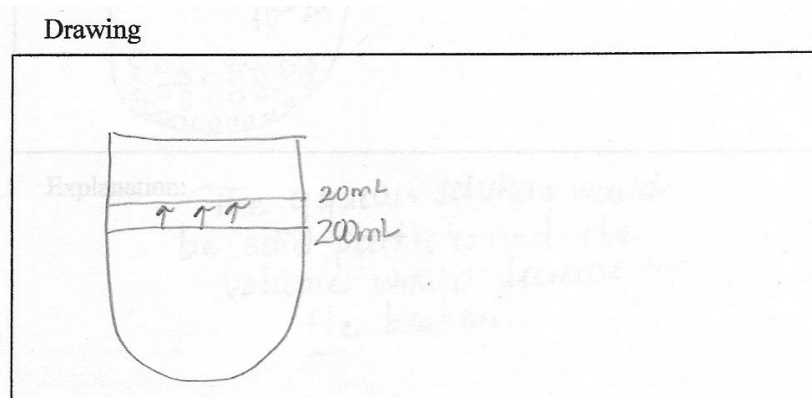
Table 4.10 Thematic Categories of Participants' Drawings of the Dissolution of Lead (II) Nitrate

<i>Thematic Category</i>	<i>Number of Responses</i>
Change in state	3
Creation of new compounds through combination of solid and water	3
Separation of water into components	4
Separation of solid into incorrect or partially correct components	7
Separation of solid into correct components with correct charges	1
Macroscopic representation	5

Note. The number of responses does not total 12 since the responses could be placed in multiple categories.

Susan (P2) continued to show a unique mental model of dissolving and melting. In addition to representing melting, Susan's drawing (Figure 4.16) is another example of a

macroscopic representation. She attempted to draw a molecular representation after repeated questioning from the researcher. Susan's drawing of the dissolution of lead (II) nitrate is essentially identical to her drawing of the dissolution of potassium iodide as seen in the following excerpt:



Explanation:

As the solid $PbNO_{32}$ melts and dissolves in the liquid the volume of the beaker increases.

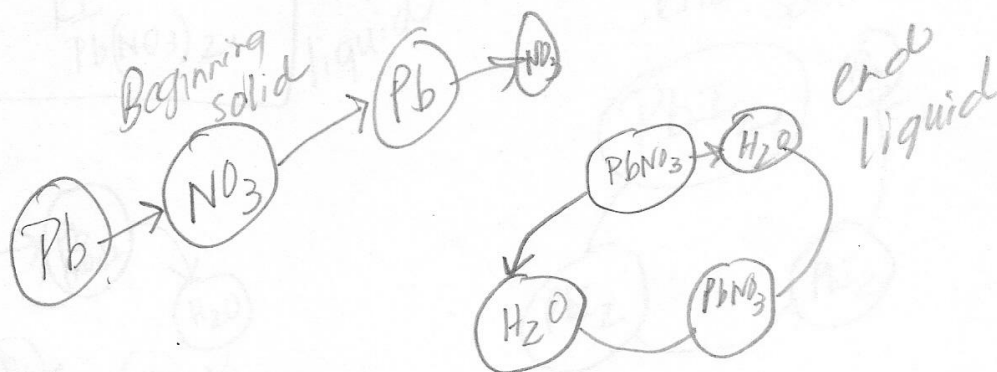


Figure 4. 16 Susan's Dissolution of Lead (II) Nitrate Drawing

P2: Maybe it...maybe it was the same way, maybe you had umm, the lead connected to a nitrate molecule and then you had it connected to another lead and then to another nitrate and this was the beginning and it was a solid and

then toward the end you would have these molecules here and then you would have the water, but they would all be liquid (*continues drawing and labeling*) and this would be the end. All the particles, I guess all the...all the solution would be there but it would be a liquid solution now, not just a solid.

Two examples of drawings and interview excerpts illustrate the category creation of new compounds through combination of the solid and water follow. In the first example, Jane's (P1) drawing (Figure 4.17) also demonstrated the category of separation of water into its components.

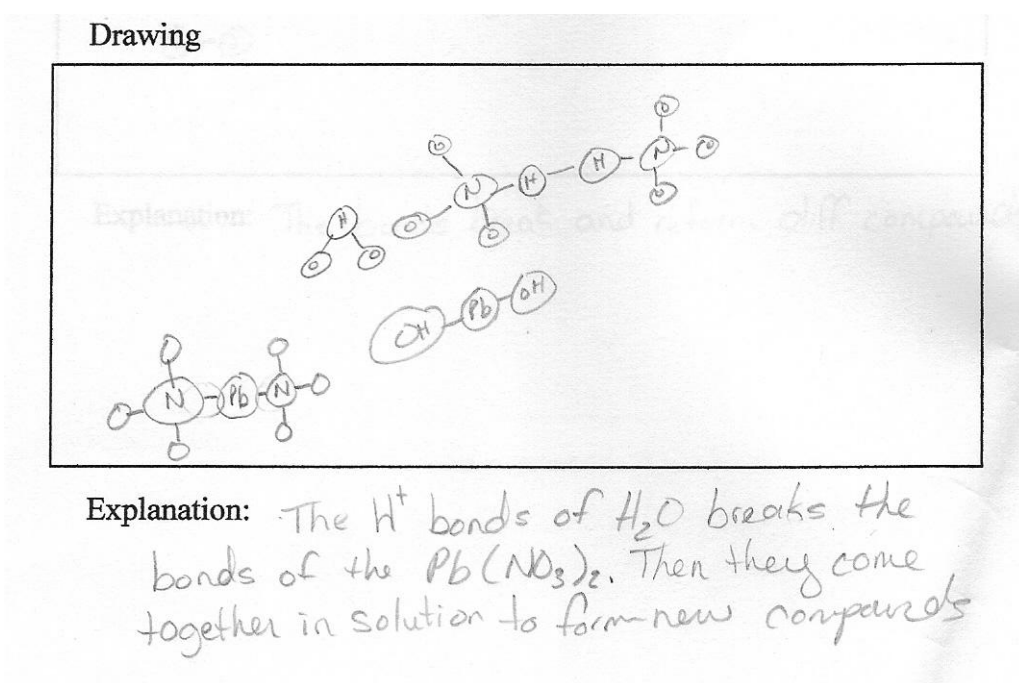
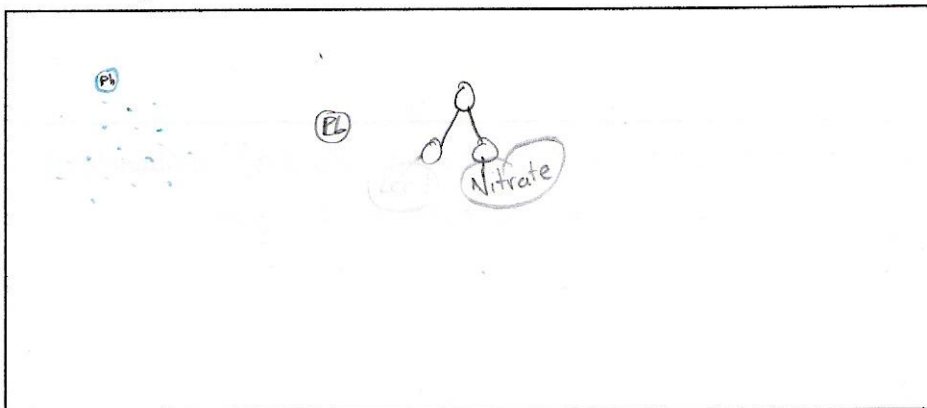


Figure 4. 17 Jane's Dissolution of Lead (II) Nitrate Drawing

- R: Okay, and then the same thing here (*pointing to drawing*) if you would explain drawing for me please?
- P1: It just shows where we had our molecule of the solid lead two nitrate and we have...there are more water molecules come together and break apart and the two nitric acids and my one lead hydroxide

In this second example of creation of new compounds through combination of the solid and water, Teresa (P8) does not separate water into its components in her drawing (Figure 4.18).

Drawing



Explanation: Lead Separates while Nitrate would attach to water molecules.

Figure 4. 18 Teresa's Dissolution of Lead (II) Nitrate Drawing

- R: Okay. So, on this one you are saying the three circles represent what?
- P8: Water.
- R: Water. Okay. So this circle with lead just represents lead.
- P8: Umhuh.
- R: You are saying that it is doing what?
- P8: It is bonding. Ohh, these two would bond together (*paper is out of view of camera*).
- R: Okay. I just want to make sure I am interpreting it correctly. So what are you saying would bond together?
- P8: Um, just the lead would be...I think the lead would be by itself and the nitrate would be attached to water because...
- R: So the lead would be by itself.
- P8: Yeah, the lead would be by itself.
- R: The nitrate would attach to the water.
- P8: Umhmm

Jane's and Teresa's excerpts and diagrams illustrate a common misconception seen throughout the interviews in which dissolution is viewed as a type of chemical reaction in which the solid breaks down and then bonds with either the water or components of the water to form entirely new compounds.

Seven participants' drawings were categorized as separation of solid into incorrect or partially correct components. In each of these cases, the participants illustrated that lead (II) nitrate breaks down, but typically did not include charges or had incorrect charges in their drawings. Wendy's (P6) drawing (Figure 4.19) is an example of this category. Wendy's drawing includes an incorrect charge on the lead ion, but represents nitrate as having no charge. She also separates a hydrogen ion from water in her drawing. Her written explanation of the drawing includes a positive charge on the nitrate. Wendy demonstrates an incomplete understanding of ionic charges.

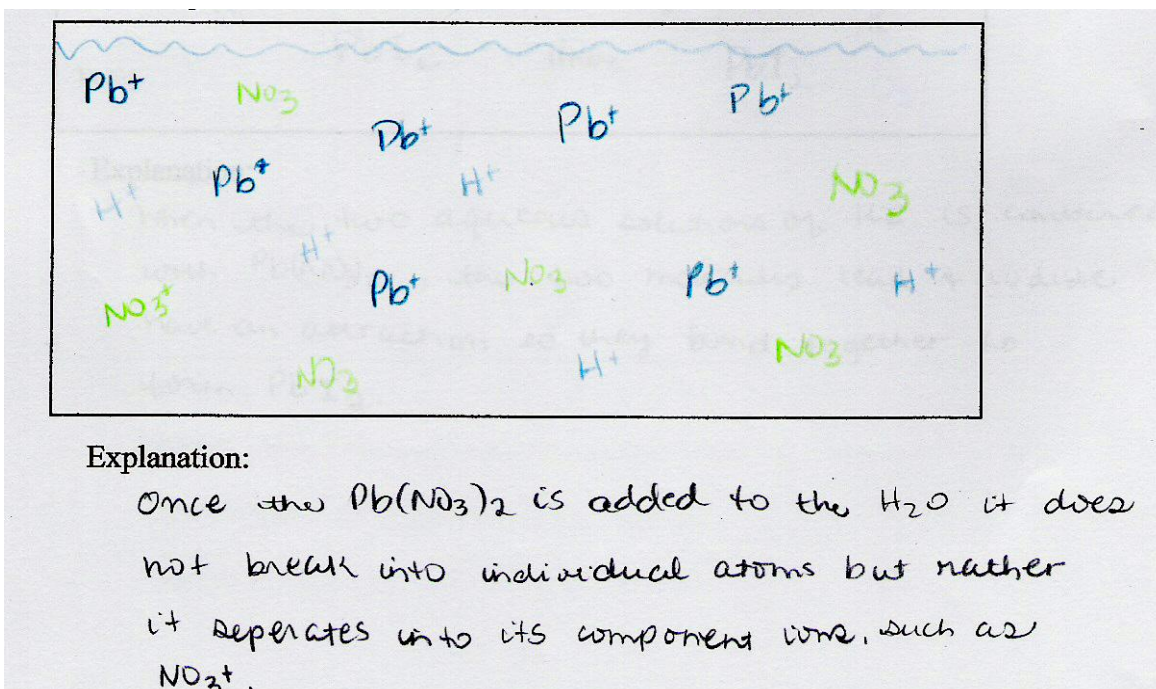


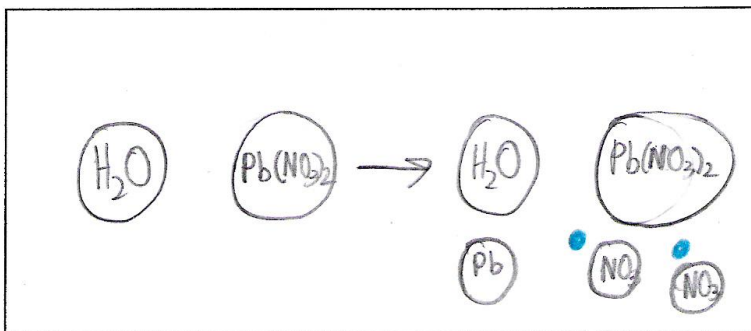
Figure 4. 19 Wendy's Dissolution of Lead (II) Nitrate Drawing

R: Okay, then let's talk through your drawing on #6.

P6: The same as with the previous drawing that I still have my NO_3^- which I said is my component ion dissolved from my lead.

Once again, William (P12) is the only participant whose drawing (Figure 4.20) was categorized as separation of solid into correct components with correct charges. Although his written explanation of the drawing matched his initial multiple choice response, his explanation during the interview demonstrated his mental model based upon solubility rules which dictate the behavior of ionic solids in water. Although William understands that the solid breaks apart into charged particles, he continues to use the incorrect particle level terminology in his explanations. His drawing and interview excerpt follow:

Drawing



Explanation:

Lead(II) nitrate melts while in water. Lead(II) nitrate as a molecule remains intact.

Figure 4. 20 William's Dissolution of Lead (II) Nitrate Drawing

- P12: My drawing, this (pointing to second circle from left) would remain correct but it would break apart into two molecules (adds two new circles on right side of drawing – beneath original circles) with the appropriate electron being placed...two NO_3 ... each one would have their own, they have a negative charge. They would have extra valance. I am only showing the valance. It is the assumed. These circles do not represent just a nucleus.
- R: Okay. Alright. Again, just to go back to clarify. Your reason initially for saying it melted was based on your understanding of solubility rules.
- P12: Yes. I was trying to remember my solubility rules. When lead is with something it, in my mind I don't remember many things that will dissolve but this is one of those cases. Just the image, the demonstration, it looked more like it was...it looked more weathering than anything else. Um, due to the stirrer I don't know how...if the stirrer wasn't there and someone could watch it for longer they would realize it is not weathering. It is actually dissolving. But for practical reasons you need the stirrer because you simply can't wait for it dissolve.

Dissolution of Sodium Hydroxide

Table 4.11 shows the frequency of initial responses to the multiple choice question on the dissolution of sodium hydroxide that were later changed by the participants. It is worth noting that this data differs from the initial responses of the previous two ionic solids in that none of the participants who chose melts as their initial choice changed that answer.

Participants who changed their initial responses about the dissolution of sodium hydroxide appear to be uncertain regarding the correct terminology to be used at the particulate level, as indicated by the data in Table 4.11.

Table 4.11 Initial Multiple Choice Responses for Dissolution of Sodium Hydroxide

<i>Multiple Choice Response</i>	<i>Number of Responses Initially Selected</i>
It melts into the liquid phase	0
It separates into the individual molecules	3
It separates into its component ions	0
It breaks apart into individual atoms	1

Note. The number of responses in this table does not total 12, since some participants did not change their initial answer choice.

The dissolution of sodium hydroxide was the only dissolution phenomenon in which a participant changed an initial response of separating into components to a final response of melting. Jane (P1) changed her initial response of separating into individual molecules based upon the macroscopic properties observed. Jane appears to be influenced by schlieren in the videos of potassium iodide and sodium hydroxide. Figure 4.21 is a screen shot of the sodium

hydroxide video where Jane pointed to the schlieren and indicated it looked like the solid was melting. An excerpt of Jane's interview in which she explains her final answer choice follows:

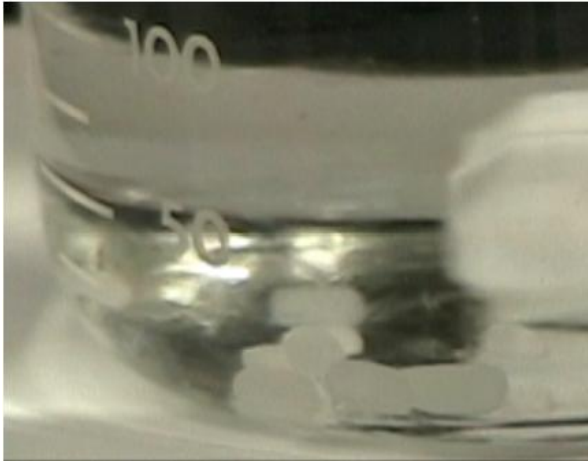


Figure 4. 21 Screen Capture of Dissolution of Sodium Hydroxide

- R: Okay, let's move to the next video, okay, so for number 9 why did you select answer A?
- P1: Because the solution really didn't go anywhere, umm, like it melted, all that happened to me was that the sodium changed states, so that's why I said it melted because, go ahead...
- R: I was going to say let's do the same thing again, let's look at that video and kind of point and indicate what it is that is making you think it's melting (*Plays video*)
- P1: And do you see how it just kind of seems like it's melting. I guess because it kind of looks like ice cubes.
- R: Well umm, I was going to say as you were pointing is there something?
- P1: There's like a ...what would you call it? But you can see the, the, I can't explain it...it looks like a ...you know it's not water coming off it , it's thicker... (*pointing to schlieren*)

Table 4.12 shows the frequency of final responses to the multiple choice question regarding the dissolution of solid sodium hydroxide. One third of the participants believed

that solid sodium hydroxide melts into the liquid phase when placed in water. As was evidenced in Jane's previous interview excerpt, a common reasoning for selecting melting as the answer corresponds to participants focusing on macroscopic properties.

Table 4.12 Final Multiple Choice Responses for Dissolution of Sodium Hydroxide

<i>Multiple Choice Response</i>	<i>Number of Responses</i>
It melts into the liquid phase	4
It separates into the individual molecules	3
It separates into its component ions	5
It breaks apart into individual atoms	1

Note: The number of responses does not total 12 since one participant selected multiple answers.

Once again, participants were asked to write an equation representing solid sodium hydroxide being placed in a beaker of water. The resulting equations were sorted into six thematic categories. The first five categories were the same as those used for the dissolution of potassium iodide and lead (II) nitrate: 1) change in state, 2) creation of new compounds through combination of the solid and water, 3) separation of water into components, 4) separation of solid into incorrect or partially correct components, and 5) separation of solid into correct components with correct charges. The hydroxide polyatomic ion appears to have influenced how participants completed their equations. While none of the participants separated the polyatomic ion nitrate into its constituent elements for lead (II) nitrate, five participants state that the polyatomic ion hydroxide would separate during the dissolution process. As a result, a sixth category, separation of the polyatomic ion into its constituent elements, was added for the analysis of the sodium hydroxide equation data. Table 4.13

includes the number of responses in each category along with examples of students' equations. Examples of each category of responses are illustrated in the following interview excerpts.

Jane's (P1) equation (Figure 4.22) and explanation demonstrates her mental model in which the solid is changing state. This is the only video where Jane represents a change in state in her equation. Her previous equations were examples of combination of the solid and water to form new compounds. Something about the sodium hydroxide confuses Jane's understanding of dissolution. Based on her explanation of the melting multiple choice answer and her subsequent pointing to the schlieren in the video, the researcher suspects that the schlieren influenced Jane's reasoning. Schlieren was present in all four videos of solids dissolving, but it was extremely noticeable in the dissolution of the sodium hydroxide. Her equation and explanation during the interview follows:

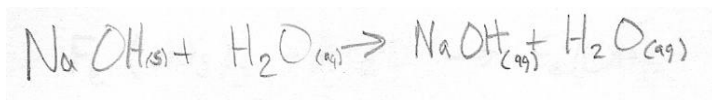


Figure 4. 22 Jane's Dissolution of Sodium Hydroxide Equation

R: ...and so again, if you would explain your equation

P1: Okay, pretty much I have the solid sodium hydroxide along with the aqueous water, over here I just when it comes back together its changed state and it's now aqueous sodium hydroxide in water.

Jasmine's (P9) equation (Figure 4.23) and interview excerpt is an example of three different categories: creation of new compounds through the combination of the solid and water; separation of water into components; and separation of the polyatomic ion into its constituent elements.

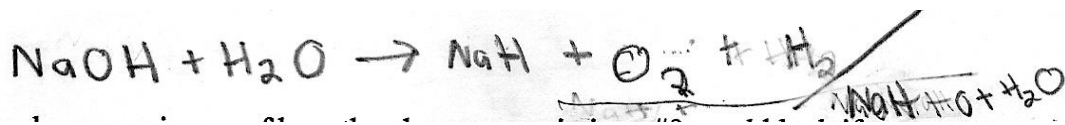


Figure 4. 23 Jasmine's Dissolution of Sodium Hydroxide Equation

- P9: So sodium hydroxide with water. (*pauses a second*) I am not sure because I have seen this equation before. So in my mind I am like okay NaH, sodium with hydrogen... (*pauses several seconds*) Okay sodium to hydrogen... (*pauses a few seconds adds O₂ and H to products in equation*) So some oxygen is going to be released.
- R: Okay.
- P9: As well as hydrogen.
- R: Okay.
- P9: (*mumbles to self*)
- R: Alright.
- P9: (*pauses several seconds erases H, re-writes H₂ in equation*)
- R: What are you thinking about?
- P9: I am thinking about... I know oxygen is going to be released but you have got to have three hydrogens on the product side. That is what you started with... (*pauses*) I believe oxygen is going to be released by itself. But I am not sure what I should do with those two hydrogens. I was like... Gosh, (*laughs*). I am going to leave it like that.

Five participants' equations were categorized as separation of the solid into incorrect or partially correct components. Ben's equation (Figure 4.24) is an example of the separation of the solid into incorrect or partially correct category and separation of the polyatomic ion into its constituent elements. Ben's explanation during the interview was also categorized as creation of new compounds through the combination of the solid and water.

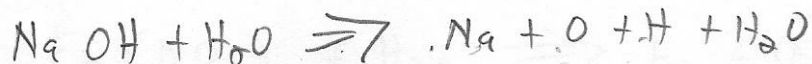


Figure 4. 24 Ben's Dissolution of Sodium Hydroxide Equation

- P5: A little bit of my chemistry is coming back to me, of course... (*pauses*) There is nothing that I could really see that was being formed out of it. In the final product this would once again be the start of the reaction and this would be the end of the reaction. Really this is just not something that you could see but

I would just imagine that the sodium hydroxide would look something like this at the beginning. If we could see it under the microscope it would look something like this at the end if they all had separated. I am starting to think a little deeper into the reactions of what would happen. I am not even going to scratch that out because that might be a little bit more accurate. What you have is separation of sodium to the oxygen to the hydrogen and the H₂O is still there. In fact, some of the H₂O molecules would have had to be broken and recombined with some of this other molecules, probably come up with some O₂s, come to think of it, since that is more natural state for oxygen.

Two of the participants, Kim (P7) and William (P12) provided equations that are accurate and were categorized as separation of the solid into correct components with correct charges. Kim's (P7) equation (Figure 4.25) and interview excerpt follows:

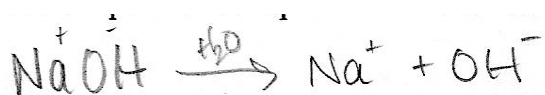


Figure 4. 25 Kim's Dissolution of Sodium Hydroxide Equation

- R: With your equation here, I am curious, I see this time you have written the H₂O over the arrow. What do you mean there?
- P7: Oh, it is just the sodium hydroxide was dropped into the water just like you said on the video so I just stuck the H₂O because my elementary chemistry is coming back to me.
- R: Okay. Alright. So what does that mean to you?
- P7: It means that sodium hydroxide is put into water. As a result, it was pulled apart into its constituent ions-the positive sodium and the negative hydroxide.

William's (P12) equation (Figure 4.26) is also accurate and his explanation shows evidence of his ability to use multiple representations to explain a chemical phenomenon. Without being asked by the researcher, William explained his chemical equation by pointing and referencing his drawing of the same phenomenon.



Figure 4. 26 William's Dissolution of Sodium Hydroxide Equation

P12: Very simplistic. They are sharing an electron (*pointing to drawing*). They break apart. My hydroxide has the extra electron and the sodium it is not indicated but this would have a +1 charge. To indicate that I would have to draw extra electrons and then you would have to double check that there is one less. So that would actually over complicate the picture.

Table 4.13 Thematic Categories of Participants' Equations Representing Dissolution of Sodium Hydroxide

Thematic Category	Number of Responses	Examples
Change in state	1	$\text{NaOH}_{(s)} + \text{H}_2\text{O}_{(aq)} \rightarrow \text{NaOH}_{(aq)} + \text{H}_2\text{O}_{(aq)}$
Creation of new compounds through combination of solid and water	5	$\text{NaOH} + \text{H}_2\text{O} \rightarrow \text{NaO}_2\text{H}_3$
Separation of water into components	2	$\text{NaOH} + \text{H}_2\text{O} \rightarrow \text{NaH} + \text{O}_2 + \text{H}_2$ $\text{NaOH} + \text{H}_2\text{O} \rightarrow \text{NaH} + \text{O}_2 + \text{H}_2$
Separation of solid into incorrect or partially correct components	5	$\text{NaOH} + \text{H}_2\text{O} \rightarrow \text{Na}^+ + 2\text{OH}^- + \text{O}_2 + \text{H}^+$ $\text{NaOH}_{(s)} + \text{H}_2\text{O}_{(w)} \rightarrow \text{Na} + \text{H}_2\text{O}_2$ $\text{Na} + \text{O} + \text{H} + \text{H}_2\text{O}$
Separation of solid into correct components with correct charges	2	$\overset{+}{\text{Na}}\overset{-}{\text{O}}\overset{-}{\text{H}} \xrightarrow{\text{H}_2\text{O}} \text{Na}^+ + \text{OH}^-$
Separation of polyatomic ion into constituent elements	5	$\text{NaOH}_{(s)} + \text{H}_2\text{O}_{(w)} \rightarrow \text{Na} + \text{H}_2\text{O}_2$ $\text{Na} + \text{O} + \text{H} + \text{H}_2\text{O}$

Note. The number of responses does not total 12 since the responses could be placed in multiple categories

As with the previous dissolution videos, participants were asked to draw an image representing the phenomenon of solid sodium hydroxide being placed in a beaker of water as if it were looked at with an extremely powerful scope that would allow the viewer to see each component separately. The pictures were sorted into seven thematic categories. The first six thematic categories were the same as those used for the dissolution of sodium hydroxide equations: 1) change in state, 2) creation of new compounds through combination of the solid and water, 3) separation of water into components, 4) separation of solid into incorrect or partially correct components, 5) separation of solid into correct components with correct charges, 6) separation of polyatomic ion into its constituent elements. The seventh category, macroscopic representations, has been used in analyzing the previous drawings. Table 4.14 includes the number of responses in each category.

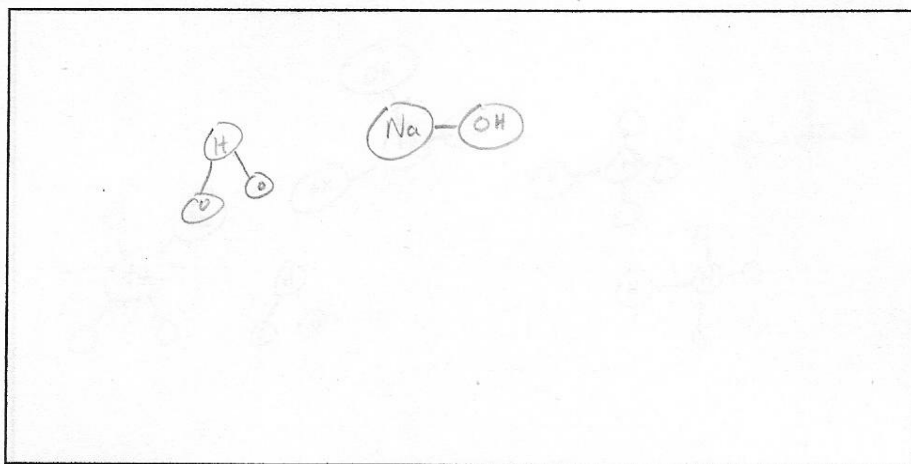
Table 4.14 Thematic Categories of Participants' Drawings of the Dissolution of Sodium Hydroxide

<i>Thematic Category</i>	<i>Number of Responses</i>
Change in state	2
Creation of new compounds through combination of solid and water	2
Separation of water into components	2
Separation of solid into incorrect or partially correct components	6
Separation of solid into correct components with correct charges	2
Separation of polyatomic ion into constituent elements	3
Macroscopic representation	2

Note. The number of responses does not total 12 since the responses could be placed in multiple categories.

Examples of the various categories of drawings are illustrated in the following interview excerpts. In Jane's (P1) drawing (Figure 4.27) and explanation, she represents the dissolution of sodium hydroxide as a change in state from a solid to a liquid. Although Jane has indicated that the previous ionic solids have broken down when placed in water, the prominence of schlieren appears to have influenced her mental model regarding the dissolution of sodium hydroxide.

Drawing



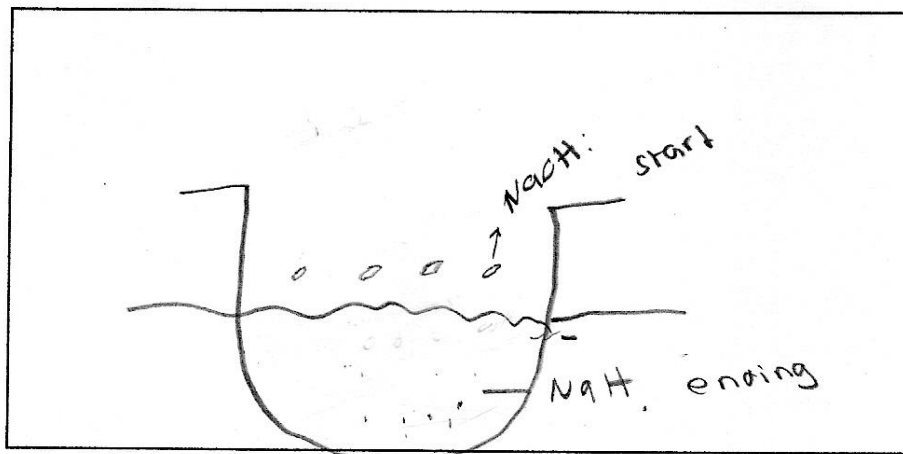
Explanation: H_2O is polar where $NaOH$ is non-polar.
no rxn takes places. It just changes to its
liquid state.

Figure 4. 27 Jane's Dissolution of Sodium Hydroxide Drawing

- R: Okay...all right and in your drawing here...
- P1: It's just two molecules (*laughs*), it just the same thing either way.
- R: Okay, so your drawing just shows what they're producing, right?
- P1: Correct
- R: Okay
- P1: And so I kind of said like water was polar where the sodium hydroxide isn't, so no reaction takes place. It just changes its state.

Jasmine's (P9) drawing (Figure 4.28) of the dissolution of sodium hydroxide and explanation is an example of several thematic categories. In the interview, Jasmine explained separation of the solid into incorrect or partially correct components, separation of the polyatomic ion into its constituent elements, and macroscopic representations. As mentioned earlier, throughout the interview Jasmine attempted to reconcile her mental model with her various representations. This excerpt is an example of Jasmine moving from a novice level of understanding towards an expert level of understanding through her attempts to reconcile discrepancies between her multiple choice answer, chemical equation, and drawing.

Drawing



Explanation: The microscope would show the individual molecules of NaOH.

Figure 4. 28 Jasmine's Dissolution of Sodium Hydroxide Drawing

- R: Okay. So let's talk about your drawing here. Like you have done on the other ones if you will label for me what the circles mean, what they represent to you.
- P9: This represents sodium hydroxide.
- R: Okay.

P9: Like before you see in a microscope and then down here it is still mixed inside there.

R: So all of these circles would represent...

P9: Umhuh. Sodium hydroxide.

R: That we started with?

P9: That we started with.

R: Okay. So what would it look like afterwards?

P9: It would be mixed in the solution. You would not be able to see it.

R: We wouldn't be able to see anything at the end?

P9: Yeah, anything at the end.

R: Okay. Even with a very, very powerful scope?

P9: Ohhh, well with a powerful microscope you would be able to see (*pauses*) just like little spots (*adds tiny dots to bottom of drawing*).

R: What would the little spots represent?

P9: (*pauses*)

R: Okay. Do you mind labeling? So this is like the beginning and this down here would be the end? Would you mind labeling representing as the beginning and the end of the video?

P9: (*labels*) I am going to get rid of this there. (*erases middle of drawing; adds squiggly line to drawing*) This is when it is first placed into the solution and then this would be the ending under a microscope.

R: Okay. What are you thinking about now?

P9: The equation. (*pauses*)

R: What about it?

P9: Thinking it is like wrong. Like I was thinking well water still...could water still be a product. (*pauses*) I don't know.

R: Okay.

P9: I will leave it like that.

R: So you think that's right? That is where it makes sense to you?

P9: No it doesn't make sense to me.

R: So what are you thinking that you need to do differently then?

P9: (*pauses*) I think it's gonna...I don't think you are going to be able to see anything. Well you will, I don't think you can see it then, you still aren't going to be able to separate. If you can see in the microscope separation, then I am thinking there should be...If it dissolves it is still going to be a liquid form. So I am trying to picture how it would look under a microscope. It would be...some oxygen is going to be released. I am thinking I want to put for the second equation.

R: Umhuh.

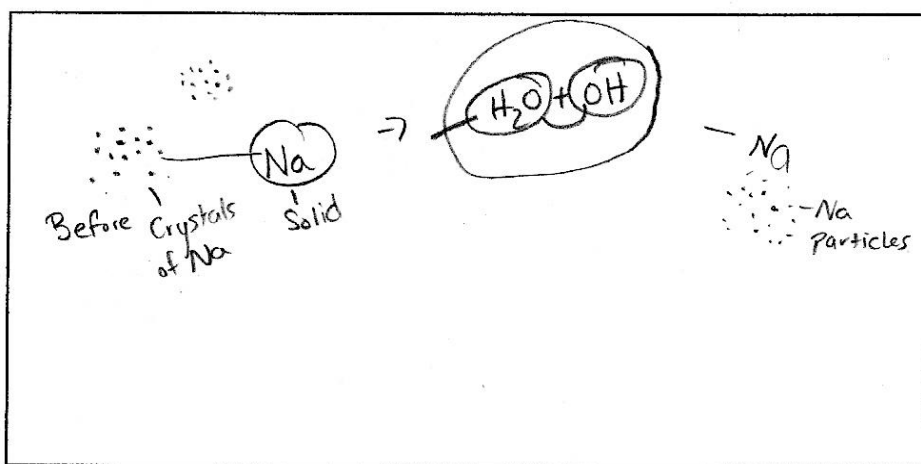
P9: (*talks herself through equation; draws a line under first equation*) NaOH here...

R: So why are you saying for the second one, you are saying it would be NaOH plus oxygen plus H₂O.

- P9: Ohh, not OH. (erases OH from and replaces with H in equation)
 R: So $\text{NaH} + \text{O} + \text{H}_2\text{O}$, your reasoning for changing that?
 P9: Because water is still present.
 R: Water is still present. Okay.
 P9: I have still got some oxygen that is being released so.

Teresa's (P8) drawing (Figure 4.29) and written explanation is an example of the category of creating new compounds through a combination of the solid sodium hydroxide and the water.

Drawing

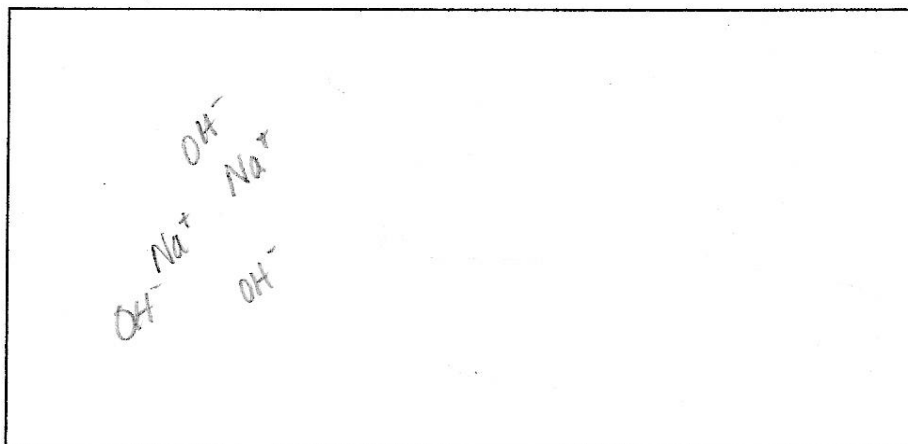


Explanation: Sodium will break or split from hydroxide, which will bond to the H₂O molecules.

Figure 4. 29 Teresa's Dissolution of Sodium Hydroxide Drawing

As seen in the dissolution of sodium hydroxide, Kim (P7) and William (P12) equations represent an accurate mental model in which the solid separates into its constituent ions with the correct charges. Kim's drawing (Figure 4.30) and explanation of the dissolution of sodium hydroxide follows:

Drawing



Explanation:

Na and OH ions floating in soln.

Figure 4. 30Kim's Dissolution of Sodium Hydroxide Drawing

- R: Okay. Alright. Do you want to talk through your drawing with me?
- P7: Once the NaOH was dropped into the water, it separated into its constituent ions, and they dispersed throughout the water. I mean I only put a small section here but it should essentially cover the whole little area here. They would just be dispersed within the water. It would be a solution.

Dissolution of Iron (III) Nitrate

Three participants initially selected an answer for the multiple choice question related to the dissolution of iron (III) nitrate and changed that response after providing written explanations of the accompanying drawing or oral explanations during the interview. Table 4.15 shows the frequency of initial responses later changed by those participants. As was seen with the dissolution of the sodium hydroxide and now in the iron (III) nitrate, changes to initial multiple choice answers appear to indicate an uncertainty or confusion regarding the appropriate particulate level terminology.

Table 4.15 Initial Multiple Choice Responses for Dissolution of Iron (III) Nitrate

<i>Multiple Choice Response</i>	<i>Number of Responses Initially Selected</i>
It melts into the liquid phase	0
It separates into the individual molecules	2
It separates into its component ions	0
It breaks apart into individual atoms	1

Note. The number of responses in this table does not total 12, since some participants did not change their initial answer choice.

Wendy (P6) illustrated in the following interview excerpt terminology has influenced her reasoning. In this particular exchange, Wendy is affected more by the term “component” than the term ion. Wendy appears to think that a polyatomic ion would be a component ion, while a monatomic ion would be an individual ion.

- R: Okay. Alright. So let’s look at the fifth video here. This was the iron III nitrate. You again have selected B that it separates into individual molecules.
- P6: Can we change that?
- R: If you want to.
- P6: I want to change my answer to component ions (*erases B and circles C*). I just basically have come to that reasoning based on that my NO_3 is a component. It has not been separated into individual ions like the iron ion is.

Table 4.16 provides the frequency of final responses to the multiple choice question about the dissolution of solid iron (III) nitrate. As seen with the previous three ionic solids, macroscopic observations influence participants. The dissolution of iron (III) nitrate appears to follow this same pattern, especially, since its solution is the only one in which a color change occurs. Jasmine (P9) explained how the color change impacted her reasoning. As seen in Jasmine’s sodium hydroxide exchange, she continued to attempt to reconcile her

responses and various representations of the phenomenon. In this excerpt, Jasmine automatically refers to her equation to guide her explanation of her multiple choice answer.

- P9: I said it melts into liquid phase because it changed the color of the water. So it just kind of came together.
- R: So it changed the color of the water. When you are saying it just came together, what is the “it” you are referring too?
- P9: Oh, that is the way it just completely dissolved. The iron nitrate completely dissolved into the water to form just one compound.
- R: What one compound did it form?
- P9: Um, (*pauses a few seconds*) Gosh, (*pauses and mumbles to self*). Iron nitrate placed into water. Um, (*pauses*) I just think that is completely wrong.
- R: Okay. So what do you think is going on then?
- P9: I think the iron three (*pauses draws line and adds Fe^{+3} under the line in the equation*). I am not sure what is wrong with it. I just don’t actually, I mean, um, I am actually not sure just to be honest.

Table 4.16 shows the number of final responses provided to the multiple choice question about the behavior of solid iron (III) nitrate as it is placed in a beaker of water.

Table 4.16 Final Multiple Choice Responses for Dissolution of Iron (III) Nitrate

<i>Multiple Choice Response</i>	<i>Number of Responses</i>
It melts into the liquid phase	4
It separates into the individual molecules	2
It separates into its component ions	7
It breaks apart into individual atoms	0

Note. The number of responses in this table does not total 12, since one participant selected multiple final answers.

As seen in Jasmine's (P9) previous interview excerpt, it appears that the macroscopic characteristics of this particular phenomenon influenced several participants. Samantha (P3) explained how the observable properties influenced her answer choice.

R: Okay, so let's look at the next one here...all right when the solid iron III nitrate is placed in the beaker of water, how did you come up with the answer that it's both A and B?

P3: Okay, A again because well I thought it was, first of all I put B because you have the separate, the compound breaks down but then I put A because I saw the film that remained on the bottom of the beaker, so I figured that some of, I don't really know how to put this in words, but it melted and then it just remained, I mean, it's in the liquid phase now, but some of it's...I don't know if that makes sense...so that's what I put. So I just had B and then I put A because I saw the layer.

As with the previous three ionic solids, participants were asked to write an equation that represented the phenomenon. The resulting equations were sorted into five thematic categories: 1) change in state, 2) creation of new compounds through combination of the solid and water, 3) separation of water into components, 4) separation of solid into incorrect or partially correct components, and 5) separation of solid into correct components with correct charges. Table 4.17 includes the number of responses in each category along with

examples of students' equations. Examples of each category of responses are illustrated in the following interview excerpts.

Renee's (P11) equation (Figure 4.31) and explanation is an example of two categories: creation of new compounds through combination of the solid and water and separation of water into components.

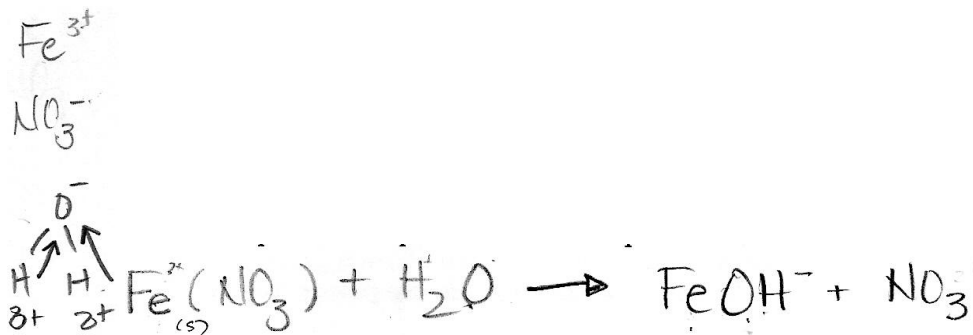


Figure 4. 31 Renee's Dissolution of Iron (III) Nitrate Equation

- R: Okay. Alright. If you will look at your equation for #13. Can you talk me through that one?
- P11: Yes. Over here (*points to writing in left margin*) I have separated each atom into their charges. Then once again that is +3 for iron and nitrate is negative 2, I think. So they are going to attract because they are negative, I mean opposites. They are going to be bonded to water. Then again water has (*draws structure of water in margin*), oxygen is negative and positive Hs, so the positive three is going to want to attract to the negative O in water to form iron oxide. Then the NO_3 s is just going to tagalong.

Samantha's (P3) equation (Figure 4.32) and interview excerpt is an example of the iron (III) nitrate solid separating into incorrect or partially correct components. While Samantha states that the solid separates into iron and nitrate, she does not include any charges in her equation. It is another example of how the observable characteristics influenced a participant's mental model.



Figure 4. 32 Samantha's Dissolution of Iron (III) Nitrate Equation

R: Okay, all right so what was your thinking here again when you wrote your equation?

P3: Okay, so this (*pointing to Fe(NO₃)₃*) is what we started with and then it broke down (*points to Fe and 3NO₃*) and I think that the color change and the film made me realize or think it was two different species I guess

Kim (P7) and William (P12) again provided equations that were accurate and categorized as separation of the solid into correct components with correct charges. Their equations and interview excerpts are not included as they do not differ from previous examples for these two participants.

Table 4.17 Thematic Categories of Participants' Equations Representing Dissolution of Iron (III) Nitrate

<i>Thematic Category</i>	<i>Number of Responses</i>	<i>Examples</i>
Change in state	0	N/A
Creation of new compounds through combination of solid and water	5	$\text{Fe}(\text{NO}_3)_3 + 3\text{H}_2\text{O} \rightarrow \text{Fe}(\text{OH})_3 + 3\text{HNO}_3$ $\text{Fe}(\text{NO}_3)_3 + \text{H}_2\text{O} \rightarrow \text{Fe}_3\text{O}_4\text{N}_3\text{H}_2$
Separation of water into components	6	$\text{Fe}(\text{NO}_3)_3 + \text{H}_2\text{O} \rightarrow \text{Fe} + 3\text{NO}_3 + \text{O}_2 + \text{H}^+$ $\text{Fe}^{3+}(\text{NO}_3)_{(s)} + \text{H}_2\text{O} \rightarrow \text{FeOH}^- + \text{NO}_3^-$
Separation of solid into incorrect or partially correct components	4	$\text{Fe}(\text{NO}_3)_3 \rightarrow \text{Fe} + 3\text{NO}_3$ $\text{Fe}(\text{NO}_3)_3 + \text{H}_2\text{O} \rightarrow \text{Fe} + 3\text{NO}_3 + \text{O}_2 + \text{H}^+$
Separation of solid into correct components with correct charges	2	$\text{Fe}(\text{NO}_3)_3 \xrightarrow{\text{H}_2\text{O}} \text{Fe}^{3+} + \text{NO}_3^-$

Note. The number of responses does not total 12 since the responses could be placed in multiple categories.

Participants were asked to draw an image representing the phenomenon of solid iron (III) nitrate being placed in a beaker of water as if it were looked at with an extremely powerful scope that would allow the viewer to see each component separately. The pictures were sorted into six thematic categories: 1) change in state, 2) creation of new compounds through combination of the solid and water, 3) separation of water into components, 4) separation of solid into incorrect or partially correct components, 5) separation of solid into correct components with correct charges, and 6) macroscopic representation. Table 4.18 includes the number of responses in each category. Examples of the various categories of drawings are illustrated in the following interview excerpts.

Table 4.18 Thematic Categories of Participants' Drawings of the Dissolution of Iron (III) Nitrate

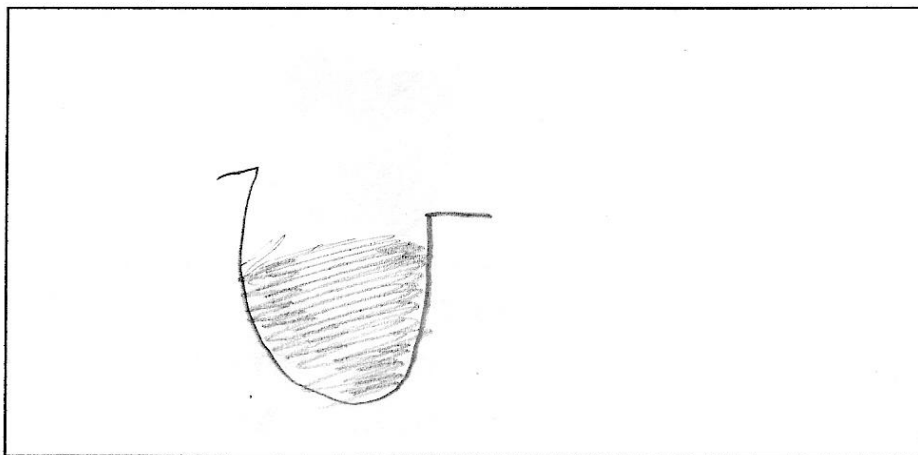
<i>Thematic Category</i>	<i>Number of Responses</i>
Change in state	3
Creation of new compounds through combination of solid and water	3
Separation of water into components	1
Separation of solid into incorrect or partially correct components	5
Separation of solid into correct components with correct charges	1
Macroscopic representation	3

Note. The number of responses does not total 12 since the responses could be placed in multiple categories.

Jasmine's (P9) drawing (Figure 4.33) and explanation is an example of both change in state and a macroscopic drawing. Her explanation also demonstrated her confusion

between the difference in physical change and a chemical change, as well as, her continued efforts to reconcile differences between her different representations.

Drawing



Explanation: This solid ~~is~~ broke down into a liquid phase changing the water into a brown-gold color.

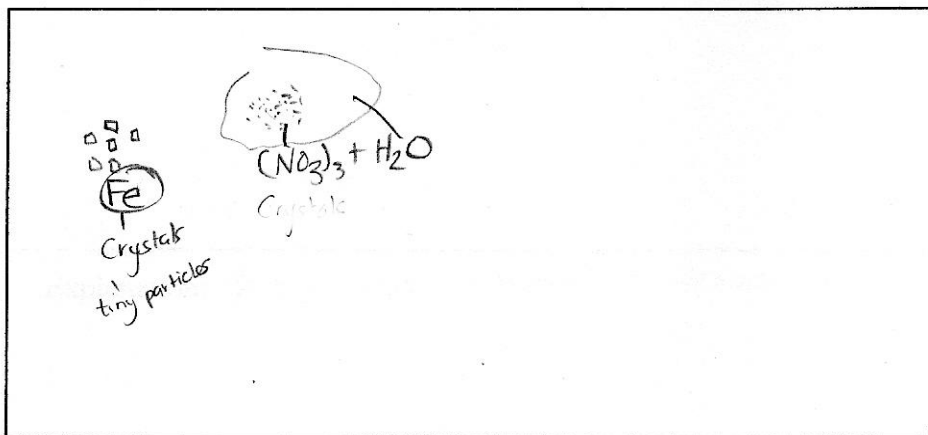
Figure 4. 33 Jasmine's Dissolution of Iron (III) Nitrate Drawing

- R: Okay. Let's talk about your drawing here. What are you representing here?
- P9: I was showing how the iron wasn't visible once it dissolved into the water. It took on a different, a liquid phase, and (*pauses and looks at equation*).
- R: Okay. You say in your explanation that the solid broke down into a liquid phase changing the water into a brown gold color. In your mind how does the color play into it? What does that color change say to you? What does that mean to you?
- P9: To me the color change shows that it was a chemical change. The chemicals just formed together. Just looking at it I was just like okay so. The chemicals just came together to make one entirely new compound.
- R: Is that what you are struggling with in the equation?
- P9: Yes.

Teresa's (P8) drawing (Figure 4.34) and interview excerpt illustrates the categories creation of new compounds through the combination of the solid and water and separation of

water into components. After separating the iron and nitrate, Teresa's explains that the nitrate will bond to water, which she refers to as nitrous oxide.

Drawing



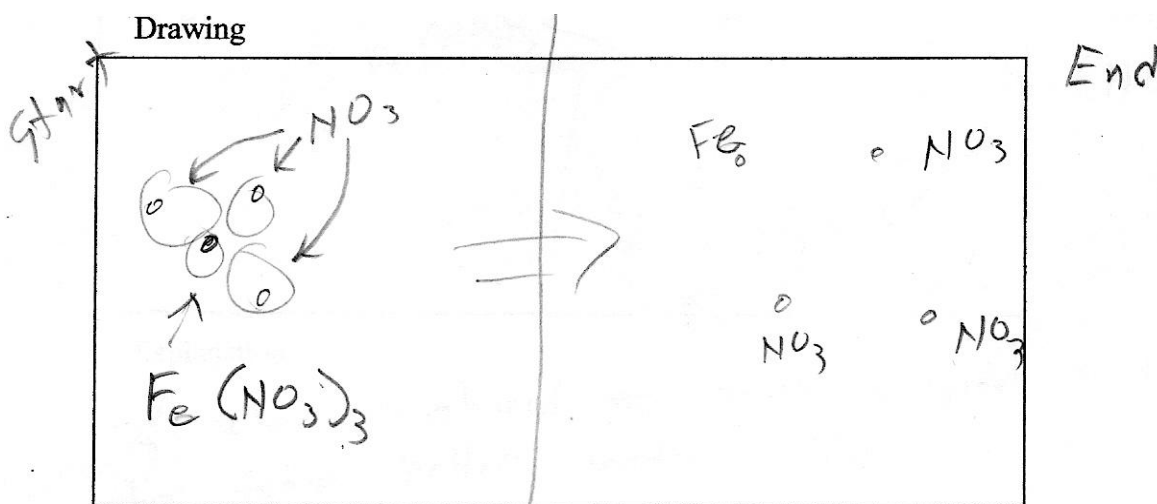
Explanation: Iron will separate from nitrate and nitrate molecules will bond to H₂O.

Figure 4. 34 Teresa's Dissolution of Iron (III) Nitrate Drawing

- R: And as you have done on the other ones will you talk about what the drawing would look like?
- P8: Okay. Under the microscope this would be iron and this would be NO₃ plus the water. I guess this is how it would look in the water, crystals.
- R: When you say crystals what state are crystals in?
- P8: Solid state
- R: Solid state
- P8: I mean, you probably, I don't know if you would be able to see the nitrous oxide, you probably would. This would be more of the crystals, tiny particles (adds labels to drawing)

Five participant's drawings were categorized as separation of solid into incorrect or partially correct components. In each of these cases, the participants recognized iron (III) nitrate breaks down, but typically did not include charges or had incorrect charges in their

drawings. Ben's (P5) drawing (Figure 4.35) and interview excerpt is an example of this category:



Explanation:

H_2O breaks bonds and $Fe(NO_3)_3$ separates into components

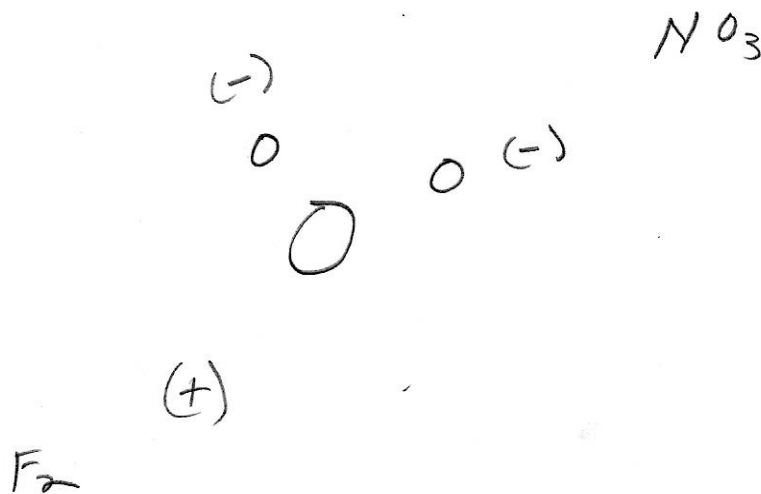


Figure 4. 35 Ben's Dissolution of Iron (III) Nitrate Drawing

- P5: Once again, maybe a little bit more of my chemistry is coming out. If this is the same (*pauses*). If I go to my drawing, (*points to start and end of reaction*) if it just separates into individual atoms then those atoms are all going to be ions because they are going to have an unbalanced charge. So, I think C is a little bit better answer for that. This is how I perceived it and rationally came up with something like this. I am sure it is a very simplified version. But the, um, put together has a compound it has a balanced charge. There is no positive or negative overall charge to the thing. There is definitely going to be either a positive or negative charge to each of these because they have separated out. Unless some of the H₂O, once again, has been split off to join with these to try to balance the charges out. Um, come to think of it, the whole polarity of water would certainly affect some of these. So they may be actual individual atoms floating around in the water just because the polarity of the water would allow them to bond with the water molecule. Once again, I have envisioned this as being (*pauses*) the iron nitrate with this being the iron and each of these being the NO₃ molecules. This representing each of these would be NO₃.
- R: Okay. You were talking about the polarity of water. Could you talk to me a little bit of what that means to, like if you were trying to define when you were saying the polarity of water?
- P5: Um, each water molecule is a polar molecule. Oxygen with two hydrogen molecules. Oxygen, if I am remembering correctly, has 6 electrons in its outer shell. Each hydrogen has one. Eight being the magic number they are sharing electrons to try to get a stable outer shell orbit. This is the configuration that a H₂O molecule creates. I believe that, I might be mistaken, this end has a degree of negativity whereas this end may have a degree of positive charge to it. That describes polarity. You have a pole on either end which would attract individual molecules or compounds to the water molecule which is what makes water the universal solvent.
- R: Could you maybe expand a little bit on how it would be attracting? You were saying as lead attracted this.
- P5: If the iron, I don't recall what the polarity of an individual iron molecule, I suppose I could look it up. (*pauses and looks at periodic table*) I will probably read this incorrectly. Iron looks pretty stable but the, well anyway. If the iron had a slightly negative charge, it would tend to be attracted to this end of the oxygen and say the NO₃, a positive charge, it would be attracted to one of these ends, oxygen molecules.

Ben's previous excerpt provided a more detailed description of his mental model about the process of dissolution. His drawing illustrated the solid iron (III) nitrate breaking

into components, albeit with no charges. However his explanation of the phenomenon at hand was richly detailed with his attempt to relate the process of dissolution to the octet rule and the polarity of water. While his initial explanation is correct in separating the solid into ions, it is not clear what he thinks happens to the water. At one point he says the water “joins” with the other substances, and at another point he says water is “attracted” to the others.

Tables 4.19 and 4.20 provide summaries of participants’ responses related to the dissolution of four ionic solids. Table 4.19 provides a summary view of participants’ initial and final multiple choice responses across the four ionic solids. As described in previous sections, a few of the participants selected one multiple choice answer initially, but later changed the response later during the task. Only 25% of the participants consistently selected the same multiple choice response for all four items. Participants’ inconsistent responses will be discussed in more detail in the following section.

Table 4.19 Prevalence of Multiple Choice Responses for the Dissolution of Four Ionic Solids

<i>Multiple Choice Response</i>	<i>Number of Responses</i>							
	KI		Pb(NO ₃) ₂		NaOH		Fe(NO ₃) ₃	
	I	F	I	F	I	F	I	F
Melts into the liquid phase (a)	6	3	1	5	0	4	0	4
Separates into individual molecules (b)	1	2	0	2	3	3	2	2
Separates into component ions (c)	0	6	0	6	0	5	0	7
Breaks apart into individual atoms (d)	1	1	1	0	1	1	1	0

Note. I= initial response; F = final response. The number of responses in each column does not total 12 since not all participants changed their initial responses and some participants selected multiple responses.

Table 4.20 provides a summary view of the prevalence of thematic categories for participants' equations and drawings across the four ionic solids. The three most prevalent categories across all four ionic solids are the combination of the solid and water to form new compounds, separation of water into its components, and separation of the ionic solid into incorrect or partially correct components.

Table 4.20 Prevalence of Thematic Categories of Participants' Equations and Drawings of the Dissolution of Four Ionic Solids

<i>Thematic Category</i>	<i>Number of Responses</i>							
	KI		Pb(NO ₃) ₂		NaOH		Fe(NO ₃) ₃	
	E	D	E	D	E	D	E	D
Change in state	1	3	1	3	1	2	0	3
Creation of new compounds through combination of solid and water	7	4	4	3	5	2	5	3
Separation of water into components	6	4	5	4	2	2	6	1
Separation of solid into incorrect or partially correct components	2	3	5	7	5	6	4	5
Separation of polyatomic ion into components	-	-	0	1	5	3	0	0
Separation of solid into correct components with correct charges	3	3	1	1	2	2	2	1
Macroscopic representation	-	2	-	5	-	2	-	3

Note. E= equation; D = drawing. The number of responses in each column does not total 12 since responses could be included in multiple categories.

Inconsistency of Participant's Mental Models of Dissolution

The previous four sections have presented data about participants' mental models regarding the dissolution of four different ionic solids. While analyzing the data, the researcher identified numerous inconsistencies in participants' mental models of the dissolution of each individual ionic solid, as well as, inconsistencies in mental models about the dissolution of ionic solids in general. The multiple choice question asked for each ionic solid was worded exactly the same with the only exception being the name and chemical formula of the ionic solid in question. A review of responses across all four multiple choice questions illustrates the inconsistency of mental models regarding the general process of

dissolving ionic solids. 75% of the participants selected different answer choices for the four multiple choice questions. The remaining 25% of the participants were consistent in their answer choice. Two of those participants consistently selected the incorrect answer choice that the solid melts into the liquid phase, demonstrating the persistence of this misconception. Only one participant consistently selected the correct answer choice that the solid separates into its component ions.

The researcher also identified numerous inconsistencies among individual participant's multiple choice responses, equations, drawings, and explanations. These inconsistencies illustrate the inability to relate multiple levels of representation to each other for the same chemical phenomenon. For each of the videos, the researcher categorized individual participant's levels of consistency. If a participant's multiple choice answer, equation, and drawing all represented the same thing, it was labeled as complete consistency between the three representations. Participants could also demonstrate partial consistency between the three representations, complete consistency between two representations, partial consistency between two representations, and no consistency between any representations. Partial consistency means a majority of the representations match, but included minor differences such as charges. Table 4.21 illustrates the level of consistency demonstrated for the dissolution of each solid.

Table 4.21 Levels of Consistency Between Individual Participant's Responses for the Dissolution of Four Ionic Solids

<i>Levels of Consistency</i>	<i>Number of Participants</i>			
	KI	Pb(NO ₃) ₂	NaOH	Fe(NO ₃) ₃
Complete consistency between all 3 representations	3	2	4	4
Partial consistency between all 3 representations	4	6	5	5
Complete consistency between 2 representations	1	1	2	2
Partial consistency between 2 representations	4	2	0	1
No consistency between any representations	0	1	1	0

Although the number of participants who showed no consistency between representations was very small, the following excerpt from Susan's (P2) interview demonstrates her mental model toward the relationship between the different representations.

- R: Right now I'm going to ask you look back at how you wrote your equation and what you've drawn...how do those two relate to each other?
- P2: (*pauses*) Say that again now
- R: How, is there a connection between the equation that you wrote and to this drawing you just drew for me of what you think happens from the beginning to the end?
- P2: (*pauses*) No, because I'm saying in the beginning I'm saying all we've got is the sodium hydroxide molecules and in the end we've got sodium and water and up there I said you've got sodium and water and it combines together to give us this here (*pointing to NaOH in equation*). So no, I wouldn't think it does because for me this was like the beginning which I would say this (*pointing to reactants*) in my equation was the beginning and that (*pointing to product*) would be the end and I don't think so. Well, I guess if you look like, well, you've got the same molecules in the beginning and the same molecules in the end, but it might be two different ...two different solids or two different chemicals...do you understand what I'm saying, probably not?

In this exchange, Susan says that there is no relationship between the equation and drawing of the chemical phenomenon. While this is not typical of all the participants, it suggests a gap in Susan's mental model of dissolution. Jasmine (P9) initially did not show consistency between the three representations. However, during the interview when given the opportunity to explain her reasoning, Jasmine frequently looked to her other representations to help her make sense of the phenomena. The researcher observed that Jasmine answered the questions on the questionnaire in the order they appeared for the first dissolution video. However, on the remaining three dissolution videos, Jasmine skipped the multiple choice item and worked on the equation and drawing prior to selecting a multiple choice response. The researcher observed Jasmine looking back and forth between the equations and drawings while completing the tasks. This behavior suggests that Jasmine may be developing a more complex mental model of dissolution throughout the process.

Differences in the Ionic Solids

As a follow-up question during the interview, the researcher asked all but one of the participants if there was a difference between the four ionic solids shown dissolving in the videos. Susan (P2) was not asked this question since she consistently selected the same response that the solids melted. The remaining 11 participants selected different answers to the four multiple choice questions, so the researcher used their different answers as the basis for the question. Based on interview transcripts, participant's responses were placed in one or more of the following thematic categories: 1) structure of the ion, 2) particulate level terminology, 3) role of water, and 4) macroscopic. The structure of ion category included responses in which participants used differences in ions, such as monatomic versus

polyatomic, to explain the differences in the solids. The second category, particulate level terminology, included responses involving participant's understanding or lack thereof of the terms atoms, molecules, and ions. The role of water category included responses in which participants referenced how water interacted with the different solids. The final category, macroscopic, included responses in which participants based their explanations upon macroscopic properties, such as color. The number of participant responses in each category is displayed in Table 4.22.

Table 4.22 Thematic Categories of Participant's Explanations on Differences in the Ionic Solids

<i>Thematic Category</i>	<i>Number of Responses</i>
Structure of the ion	3
Particulate level terminology	4
Role of water	5
Macroscopic	3

Note. The number of responses does not total 12 since the responses could be placed in multiple categories.

Examples of each category are provided in the following interview excerpts.

Samantha (P3) thought that the difference between the solids was related to whether the compound included monatomic or polyatomic ions, although she used different terminology to represent these types of ions.

R: okay, so now let me ask you a couple of questions with these, that I noticed that, umm, for the solids that were dissolving in water you have a couple of different answers for them, on some you had one answer on some you had two

answers, a couple you said they looked like they melted, and some you said they changed into ions, a few you said changed into molecules, umm, what do you think is the difference between those solids?

P3: Umm, can I flip back and look

R: Yeah, yeah...

P3: Umm, like okay, for some of these just had the solid but then or they were just like pure elements I guess and then this (pointing to lead two nitrate) is like the nitrate and the lead. So I think it's just depending upon the type of mixture that it was or the solid that was dropped in

R: So when you call that a pure element what do you mean by that

P3: Umm, it isn't, it's just like one

R: So you're referencing KI

P3: Right

R: So you're saying...

P3: So it's like two pure, I don't know, like, I don't know how to say this but ...there's the potassium (*pointing to K on periodic table*) you know, so it's like completely by itself and then the iodide or iodine (*pointing to I on periodic table*).

R: So how...

P3: So there's nothing else, but see here (*pointing to lead two nitrate*) you have the lead and then you have the nitrogen and (*points to O*) well, yeah, then ...I don't know how to say that.

Wendy (P6) exhibited similar reasoning in her explanation of the difference between the solids. However, her confusion appears to be over the word "component". By Wendy's reasoning, a polyatomic ion is a component ion and a monatomic ion is an individual ion.

R: Okay. Alright. In looking back now, on some of the, thinking about the four solids that dissolved in water, some of those you answered multiple choice questions with B became individual molecules and others you answered C that they separated into component ions. What do you think is the difference between those four different solids? We have the potassium iodide, lead two nitrate, sodium hydroxide, and the iron three nitrate. What was the difference that makes you select the different answer choice there?

P6: Well, when I had a combination of the NO_3 or OH I chose those as being component ions because they are not individual ions themselves. They are a combination of the oxygen and hydrogen. That is why that those particular ones versus the potassium separating from the ion, those were two individual molecules themselves. Something about I guess the attraction of a positive ion versus a negative and they combining together. Some ions have more of an

attraction for each other of a bonding element for each other than other molecules.

Four participants demonstrated their incomplete understanding of particulate level terminology while attempting to explain the differences between the four ionic solids. These students selected multiple choice answers based on three different terms – atoms, ions, and molecules. In the following excerpt, Amanda (P4) explained how she used nomenclature as a clue to whether a substance consisted of ions or not. Specifically, she thought that the lack of a roman numeral, as used to indicate the oxidation state of a transition metal, indicated that ions were not present in the compound.

- R: Okay, and with the lead two nitrate you selected that it would be ions, so how is that one different than the potassium iodide
- P4: Well the two indicates a charge so ions
- R: Okay, so you felt that was a charge so that was an ion and if we looked at sodium hydroxide you selected individual atoms what was your reasoning, how did you think that was different than the other two solids we've talked about
- P4: versus the number one?
- R: versus the potassium iodide and the lead two nitrate, which you know have the same answer for the potassium iodide
- P4: Well the NaOH isn't charged it's neutral so it's not ions, umm, (pauses) and my formula kind of displays individual atoms except for when I get to the H_3O_2 which I'm assuming I have to break apart but I didn't cause I wasn't sure how to make it look right.

Later in the interview,

- R: Okay, let's look at your final one to see and it was ions and again how how did you make that one ions versus atoms
- P4: The three, the iron three means charge, so...

Wendy (P6) explained in the following excerpt how she has never really thought about the difference in the terms atoms, ions, and molecules.

- R: Okay. So when you look at your answer choices there, you are really looking for B, C, and D. The difference in the words really are molecules, ions, and atoms. What does those three terms mean to you?
- P6: I guess I am not very clear on the individual molecules versus the individual atoms. I guess when I see the word potassium and the word iodide that I think of those as molecules versus being individual atoms. When I see component ions I see that as a combination of the two different molecules put together.
- R: Okay. So what do you think of when you think of individual atoms?
- P6: I guess I don't really know. I have always referred to everything as being a molecule. I have not really thought about what an individual atom would be.

Ben (P5) used the terminology incorrectly when answering the question, but when asked specifically about the meaning of the terms, he was able to explain them. This is illustrated in the following excerpt:

- P5: As I mentioned earlier, they are in a compound. They are electronegatively balanced, whatever the word is. They are seeking to have no charge. If you have split them then suddenly they have a charge, um I mean, an oxygen molecule has a charge and hydrogen molecule has a charge. If you put the two together they have less of a charge.
- R: So let me ask you, do the terms, difference really between answer choice B, C, and D are the kind of final words. Can you talk to me about what you think the term molecule, ion, and atom, what those three terms mean?
- P5: A molecule is a combination of atoms. An atom is an element which cannot be theoretically subdivided any further with the exception that you can obviously lose electrons. If it has an odd number of electrons to it then it is an ion. Of course, there is the other exception, I believe those have extra neutrons added to the atom.
- R: So to clarify again what is an ion? How do you explain what an ion is?
- P5: (*laughs*) Now I am thinking some of my answers are incorrect. An ion is an atom which has either lost or gained an electron.

Five participants reference the role of water when explaining the differences between the four ionic solids. In most cases the role of water includes the bonding of the solid or its components to the water molecule. Ben (P5) and Wendy (P6) both think that the solids

actually bond to the water molecule during dissolution. Excerpts from their interviews

follow:

- R: ... Do you think, based on what you have kind of told me, can you explain, do you think that those four different solids reacted differently when they were placed in water?
- P5: Do I think they reacted differently?
- R: Right. So when the solids were placed in the water to dissolve?
- P5: I am sure based on the number of electrons they have in their outer shell they all react differently. They are probably going to want to bind. If one atom has five electrons it is going to want to bind (gain three electrons) whereas if one has seven electrons it is only going to want to add one electron. If it does form new associations with the hydrogen and oxygen from the water molecule than that is going to be different.
- R: What role do you think the water molecule plays in that as you are dropping those different substances into the water?
- P5: It probably is a better combination for each of the compounds, which is why the compounds would break apart and seek to reassociate with either the hydrogen or oxygen or the water molecule itself.
- R: Just to clarify, what do you mean when you say it is probably a better combination? What exactly do you mean by better combination?
- P5: It would provide, probably provide a more stable outer shell, more stable number of electrons and Van der Waals reactions and um, better electronegativity and all those really cool chemistry terms.

Below Wendy (P6) explains how she thinks the ions combine or attract to the actual water molecule during dissolution:

- R: So all of these solids we are putting them in the water. I would like to know what your ideas are about what role does the water play in dissolving that solid? What do you really think is going on there?
- P6: That, with putting the solids in there, um, that the water acts as a solvent, which will dissolve a solid or the solute. Once put into the water that, um, I know what I am thinking I can't quite get it out...that the, I guess, not a reaction but that the water will I guess the attraction there of the water the different positive/negative ions react with the solids in a way that will cause them to, I guess, break apart if they are combined together to break apart and combine or be attracted to another ion that is in the water itself.

In the following interview excerpts, Teresa (P8) and William (P12) explain that water breaks the bonds of the ionic solids during dissolution.

- R: Okay. Alright. Another thing that I noticed on some of your equations here you kind of talked about the water. Could you talk to me a little more about what you think the role of the water is in the dissolving?
- P8: It breaks bonds.
- R: What do you mean by it breaks bonds? If you kind of just expand on that a little bit.
- P8: It causes the...cause it is a stronger bond. The other two would be weaker bonds. It kind of pulls the other, the nitrate, it pulls that away from the solid.
- R: Okay. So you are saying it pulls it away. You are referring to the water.
- P8: Yeah, the water.
- R: Okay pulls it away. You mentioned that it had stronger bonds. How do you know about those stronger bonds? What do you mean by that, that water has stronger bonds?
- P8: Because they tend to stay together because they are, ...chemistry (*laughs*)...it is not my major. Um, cause, they are polar.
- R: Okay. Could you tell me what do you understand about the word polar?
- P8: They are alike molecules...stronger...it is just the state. The bond is stronger.

And here's William's explanation of water breaking bonds,

- R: Okay. So could you talk to me about what is the role of the water in all of these reactions? What role do you think the actual water has?
- P12: (*pauses*)
- R: Like in breaking down and dissolving the solids. What role does the water play?
- P12: Oh, so since their ionic. I am trying to remember back to my properties of water...the water molecules are polar molecules. What is happening is, because of their polarity, I think that's the correct terminology, it is pulling apart this ionic compounds because in the ionic compounds they are only balancing out their own, well unbalanced charge. When you throw in another charge, in this case the water molecules, it is pulling these charges apart. If you have two small magnets together and have a bigger magnet pull them apart. It is the same principle.

Three participant's responses were placed in the final category based upon macroscopic observations. Samantha (P3) and Jasmine (P9) both refer to observable

properties when attempting to explain differences between the four ionic solids. Excerpts illustrating this category follow:

R: Okay, how might you think it would dissociate differently ...what would be the differences?

P3: Umm, like how one of them just left the film at the bottom and how some of the others just completely like cleared up.

And another example,

R: Okay. Do you think they react differently when we actually put them in the water then?

P9: (*pauses*)

R: When you took those four solids and put them in the beaker of water, do you think that...

P9: I think that they did react differently.

R: Okay. How would you kind of explain that they reacted differently? Why they reacted differently?

P9: (*pauses*) Because for one, for some, there were a color change.

Factors Affecting Dissolution

The final three questions of the interview were designed to elicit participants' thoughts on dissolution in general. Participants were asked why they think some solids dissolve in water and others do not. They were also asked to think about and explain how heat and stirring cause a substance to dissolve faster. Responses to these questions provided a glimpse at the understanding of participants in terms of the mechanism of dissolving. Transcripts were coded and organized into four categories: 1) movement, 2) energy, 3) role of water, and 4) other. The movement category included responses that referenced collisions of particles, vibrations of particles, distribution of particles, and speed of particles. The energy category included responses that referenced energy as a reason for dissolution. The third category, role of water, included references related to the breaking of bonds by water

and polarity. The fourth category, other, was for responses that did not fit in the previous categories. The number of participants giving explanations within each of the four categories is displayed in Table 4.23.

Table 4.23 Thematic Categories of Participants' Explanations on Factors Affecting Dissolution

<i>Thematic Category</i>	<i>Number of Responses</i>
Movement	21
Energy	5
Role of water	7
Other	5

Note. The number of responses does not total 12 since the responses could be placed in multiple categories.

Interview excerpts are provided to illustrate each of the four categories. The largest number of responses was in the movement category where participants referred to collisions, vibrations, catalysts, and distribution of particles. Jane (P1) used the idea of collisions to explain the roles of heat and stirring in dissolving as shown in the following excerpt:

- R: Okay, all right you may have also noticed some solids dissolve faster when you stir and so, do you have any ideas why that may happen?
- P1: I feel like, umm, it's putting the molecules in motion...so you, you're making them ...let's see...how do I want to say that...it's like, it's almost like you're exciting them and making them react to each other faster...like, I don't want to say it's adding heat, but I mean it's exciting the molecules and crashing them into each other breaking apart the bonds faster.
- R: And what do you mean when you said a few minutes ago it makes them react faster...what exactly were you saying?
- P1: Ohh...like as far as it speeds up the rate of reaction...as far as...I don't want to say a like a catalyst, but umm I mean it almost would be cause it doesn't have any effect on the actual reaction, but it speeds it up.

- R: All right, and then finally, you may have noticed some solids will dissolve faster when we put them in warm or hot water, umm, why do you think that might happen?
- P1: I would say basically the same catalyst reaction...you're introducing something like the, I would say the warm water would lower the energy of the reaction and then that way there like it still excites the molecules, it still gets them going...it probably would work faster in my opinion than doing the stirrer faster because you have those molecules moving and crashing into each other at a higher rate and you know you're able to break the bonds more easier
- R: Okay, so does the crashing together have something to do with breaking the bonds?
- P1: I think so.
- R: Could, could you expand on that, what you think might be happening there?
- P1: Pretty much, when they like, when they crash into each other, the energy that's produced kind of breaks apart the molecules.

Jane appears to believe that collisions of particles results in the production of energy, and the energy being produced by the collisions is the energy needed to break bonds. Her response was included in both the movement and energy categories, since she believes the collisions produce energy needed to break bonds.

Five participants specifically referenced the amount of energy in the system when explaining the effects of heat and stirring on dissolution. In each of these cases, the responses were also categorized in the movement category, since energy was used to explain why the movement occurred. Teresa's (P8) response is particularly interesting as she referred to "energy molecules" in the following excerpt:

- R: Okay. You also may have noticed that sometimes solids will dissolve faster when we stir them in the water. Do you have any ideas about why that happens?
- P8: Um, I guess cause the force of....the water moving not just sitting still. Something like energy causing them to pull apart. Maybe heat would be involved in that more so if it was just...
- R: So the stirring causes...
- P8: Energy molecules to bounce around and break apart

William's (P12) response was very short, but not a surprise given his background in physics. Below is his explanation of the role of stirring:

- R: Okay. Alright. You may have also noticed that some solids dissolve faster when we stir them. Do you have an idea about why stirring them would make them dissolve faster?
- P12: You are putting energy into a system which is going to cause...you are putting energy into a system. It causes molecules to vibrate more. It is easier to break their bonds because you are putting energy to break the bonds.

Seven participant's responses were included in the role of water category. Several of the responses in this category included the idea that has been discussed previously in which water actually bonds to the solid or its components. Several participants also referenced polarity in their attempts to explain dissolution. Participants whose responses were placed in this category had previously referred to water as polar during earlier portions of the interview.

Samantha (P3) discusses why some solids dissolve and others do not in the following exchange:

- R: Okay, all right, umm, now these are actually they're not necessarily related to these (pointing to questionnaire) specific things, they're just questions in general about dissolving, umm, why do you think some solids dissolve in water and others won't?
- P3: Because it's like the whole like dissolves like
- R: So what does that mean?
- P3: So polar and depending on the polarity so if you're nonpolar...like if it was a polar substance and then since like water is polar, correct, but it just depends on whether the substance is polar or nonpolar
- R: Okay, okay, and do you want to kind of expand on what polar means?
- P3: Umm, you have like a, an uneven pull of molecules in the direction of the more electronegative.

In the excerpt below, Teresa (P8) also references polarity in her flawed explanation of why some solids dissolve and others do not. She refers to bond strength in terms of polar and non-polar, but then explains that a polar bond is stronger and therefore would stay together

when placed in water. Based on her explanation, polar molecules would not dissolve in water.

- R: When it's polar it is stronger. Okay. So I am going to ask a few more questions that don't necessarily have to do with the videos but they have to do with dissolving. What are your ideas about why some solids dissolve with water but others solid won't?
- P8: Going back to bonds, how strong their bonds are.
- R: Okay.
- P8: And that how tightly (*mumbles to self*) same thing.
- R: Okay. So you could talk to me a little bit more about how strong their bonds are and give me kind of an example of what you would think?
- P8: It is more their bonds are alike. Polar versus nonpolar, they would stay together if they were polar. If they are not polar, they would break apart.
- R: So bond strength has to do with being polar versus nonpolar. So you are saying a stronger bond is polar. Stay together or pull apart?
- P8: Stay together.
- R: Stay together. A weaker bond would be nonpolar and would pull apart. This is what you are saying?
- P8: Umhmm

Melissa's (P10) incorrect explanation of why some solids dissolve and others do not referred to the role of water in dissolution. She erroneously believed that when a solid dissolves, it is the solid breaking the bonds of the water, instead of the reverse. This is illustrated in the following exchange:

- R: Okay. Alright. I am going to ask you a few other questions that don't necessarily have to do with the videos. They are kind of in general. Why do you think some solids will dissolve in water but other solids won't?
- P10: Because maybe they can't break those bonds.
- R: What can't break what bonds?
- P10: I think some things can dissolve in water because it is able to break the bonds between the oxygen and the hydrogen. Maybe other solids can't break those bonds.
- R: Okay. So if the solid can break the bonds in the water it does what?
- P10: It dissolves.
- R: It dissolves. If the solid cannot break the bonds in the water, then you think it?
- P10: May continue to stay solid.

The question about the role of heat in dissolving seems to have supported the mental models of Susan (P2) and Melissa (P10) in which dissolving involves melting. Susan consistently throughout the entire interview explained that dissolving and melting were the same. In the following exchange, Susan used the example of snow melting when exposed to sunlight as a reference for her explanation of how heat affects dissolving.

- R: Okay...okay, and last idea here for you...you, umm, may have noticed that sometimes solids will dissolve faster if they are placed in warm or hot water ... do you have any ideas about why that might happen?
- P2: Umm, maybe because (*pauses*) I mean maybe they could go back to the actual molecule I mean some molecules could you know when heat is added they would dissolve faster than molecules that you know the higher the heat (*pauses*) let me see what I'm thinking here ...maybe some molecules would dissolve faster the more heat that is applied...and some molecules would need higher heat to cause it to melt, you know what I mean, so I guess the , the heat resistance, maybe, on certain molecules would determine how fast they melt when heat is applied to it.
- R: Okay, so what does it...I want you to ... this is kind of related to what you said earlier in the interview...you were talking about when I asked you what things mean, what it means when they melt and you gave me the example of like snow and how when it heats up it becomes liquid ... so thinking through that, and what you're talking about with the melting and the heat involved, go back and try to tie that in with this dissolving faster...
- P2: I guess depending on , you mean like, relating to the actual item or to the actual particles there ... I guess, umm, and I don't know if this is where you want me to go with it or not, but, when I think of snow and it melting (*pause*) it's made up of water, so you know I mean, it doesn't really take a, I mean when the sun comes out it's not, you know what I mean, it doesn't take but a little bit of sun and it melts and it becomes liquid, you know, I don't know if that's what I'm supposed to be saying or not.
- R: So think, okay, and that's, that's what I wanted to have here and you've said in several of these cases the solids are melting, and so we're asking you know why are they dissolving faster when placed in warm water, so how do you think that heat in that water affects the solids.
- P2: It causes them to melt faster.
- R: Okay
- P2: Is that what you wanted me to...(*laughs*)
- R: I want to know what you think

- P2: I mean I would think that, you know , I think if you gave us the same solid in cold water and the same solid in hot water or warm water, umm, I think it would the hot water would probably melt or dissolve quicker than in the cold water .
- R: Okay, and just to clarify earlier you said you think melting and dissolving are the same things, different things?
- P2: I think it's the same. I mean melting and dissolving to me is actually, it kind of means they're both changing form and so...

As seen in earlier excerpts, Melissa (P10) believed that dissolution is a two part process in which solids break down and then melt. She also included triangles over the arrows in her equations to represent heat. The excerpt below supports her mental model of a two step process.

- R: Okay. Then you may have also noticed that sometimes solids will dissolve faster if we put them in warm or hot water versus putting them in cold water. Do you have any ideas about why that happens?
- P10: The melting point of that component, the heat, makes it melt. Because you have to go from a solid to a liquid. You have to wait for that solid to form a liquid. If you add heat then it will become a liquid faster.
- R: So again you are saying that dissolving is making it go from...
- P10: Solid to a liquid.
- R: So you think it goes from a solid to a liquid when it dissolves. So if you had heat that just makes that happen...
- P10: Faster

Kim (P7) explained the role of heat and stirring in dissolving through a comparison of proteins and catalysts. It is interesting how she used terms such as “denature” to explain how collisions cause dissolution to occur faster. This is an example of a response that was included in two different categories: movement and other.

- R: Um, okay. Another thing that you may have noticed is that some solids will dissolve faster when they stir them. What are your ideas about why that happens. Why stirring them would make them dissolve faster?
- P7: It helps to denature the bonds I guess. It is easier to break if you have them moving around. They are pulling apart so they will pull apart easier and rebond.

- R: You used the term “denature the bonds”. What exactly do you mean by that term?
- P7: When we denature it takes the initial form away. It pulls apart, like denaturing a protein, it’s the same thing.
- R: Okay. So you are saying it just moves them around. What role do you think movement has in dissolving a solid?
- P7: I think if you have your stirring bar spinning in your thing and your little molecule or little ions are floating down and they are all hooked together and then suddenly they are hit by this wave (*whoosh*). It is going to just be easier for them to have a hydrogen say come in and move or hook to another ion. If it is falling this way and then you have your opposite ion over here and then there is attractive force there then they come together easier that way.
- R: Okay. Alright. The final question here. You may have noticed that some solids dissolve faster when we put it in warm or hot water versus cold water. Do you have any ideas about why that may be so?
- P7: I know temperature can catalyze certain reactions. It makes it easier for the reactions to occur, the bond to occur. I guess it could be something like that.
- R: You used the term catalyze the reactions. What does that mean exactly to you?
- P7: It facilitates the reaction. It makes the reaction easier to occur.
- R: I am trying to get you to think a little more here. How might that temperature be doing that, facilitating the reaction and making it to occur easier?
- P7: (pauses a few seconds) I guess it could be the vibration of the molecules as things heat up. Things are not stagnant. They are going to be dynamic. I guess the molecules could be vibrating, heating up. As they heat up making the bonds easier to break and reform.

Precipitation Reactions Data Analysis

Participants were shown two videos in which a precipitate formed from the combination of the previously discussed ionic solutions. Solid lead (II) iodide was formed by the reaction of aqueous potassium iodide and aqueous lead (II) nitrate. Solid iron (III) hydroxide was formed by the reaction of aqueous sodium hydroxide and aqueous iron (III) nitrate. Following each video, participants were asked to write a chemical equation that represented the phenomenon observed. Participants were also asked to draw an image of the phenomenon observed imagining that it was being viewed under an extremely powerful microscope that allowed the components to be seen separately. Participants were asked to provide a written explanation of their drawings. The researcher interviewed the participants about their answers and responses to seek additional clarification of the participants' understanding of the phenomenon at hand.

The data from the student produced equations and drawings were treated as qualitative data. All of the participants' equations and drawings were reviewed by the researcher and phrases were developed to describe the equations and drawings. All of the descriptive phrases were listed and then grouped into thematic categories. The interview data was analyzed similarly to the equations and drawings data. Interview transcripts were coded with descriptive phrases, which were later grouped into thematic categories.

Data for the precipitation of lead (II) iodide and iron (III) hydroxide follows.

Precipitation of Lead (II) Iodide

As with the dissolution of the ionic solids, participants were asked to write an equation that represented the precipitation of lead (II) iodide from the reaction of aqueous

potassium iodide and aqueous lead (II) nitrate. The resulting equations were sorted into three thematic categories: 1) double displacement, 2) water as reactant, and 3) solid as only product. The double displacement category includes responses in which participants indicated an exchange of ions between the two reactants to form two or more products. Accuracy of product formula was not considered when categorizing responses. The water as reactant category includes responses in which participants included the formula for water in the equation on either the reactant or product side. This category also includes responses in which participants indicate that water bonds with other reactants to form a product. The final category, solid as only product includes responses in which participants predicted the formation of one product, the solid. A distinguishing characteristic of the solid as only product category is that participants were not providing net ionic equations. In this category, both aqueous compounds are included as reactants and the solid is the only compound shown as a product without any mention of the spectator ions. Table 4.24 includes the number of responses in each category along with examples of students' equations. Examples of each category of responses are illustrated in the following interview excerpts.

One half of the participant's individual equations were categorized as double displacement reactions. William (P12) is the only participant who accurately represented the existence of spectator ions in his equation (Figure 4.36). Although he did not use the term spectator ion, it is clear that he understands that some ions remained in solution. His equation and explanation follow:



Figure 4. 36 William's Precipitation of Lead (II) Iodide Equation

P12: Okay. In this equation, we know a solid precipitate is formed. We have our potassium iodide and our lead nitrate in solution. They would break apart. Initially I thought it would be a simple double displacement reaction. Then I realized that no I have a precipitate formed. Those two ions would not come back together. They would remain dissolved in the solution

Table 4.24 Thematic Categories of Participants' Equations Representing Precipitation of Lead (II) Nitrate

<i>Thematic Category</i>	<i>Number of Responses</i>	<i>Examples</i>
Double displacement	6	$2KI + Pb(NO_3)_2 \rightarrow 2K^+ + 2(NO_3)^- + PbI_2$ $KI + Pb(NO_3)_2 \rightarrow PbI_2 + KNO_3$
Water as reactant	3	$KI + Pb(NO_3)_2 + H_2O \rightarrow PbI_2 + HNO_3 + K^+ + O_2$
Solid as only product	3	$KI + PbNO_3_2 \rightarrow PbI_2$

The most frequent idea in the double displacement category is aqueous potassium iodide and aqueous lead (II) nitrate react to produce two new compounds through bonding. Samantha (P3) explained how the macroscopic properties of the reaction influenced her equation (Figure 4.37) in the following excerpt.



Figure 4. 37 Samantha's Precipitation of Lead (II) Iodide Equation

- P3: Okay well this is what you started off with, the potassium iodide and you add to it the umm aqueous lead two nitrate and then so they react and then they create those two (*pointing to PbI_2 and $2K(NO_3)$*) things. Actually, yes, they create the lead iodide
- R: okay
- P3: and that (*pointing to $K(NO_3)$*) would be like the byproduct I think
- R: okay, so what do you mean by a byproduct, what does that mean?
- P3: Umm, this (*pointing to PbI_2*) I figured was the layer at the top and this (*pointing to $K(NO_3)$*) would be the things floating around in the solution

As seen in Samantha's exchange with the researcher, she believed that the components of the top layer and particles floating in the solution are different compounds. See Figure 4.38 for a screen shot of the video with the top layer and floating particles. This shot is from the last frame of the video in which the lead (II) iodide particles are settling to the bottom of the beaker. Though not stated explicitly in her interview, it would appear that Samantha's mental model of precipitation reactions includes the idea that all of the ions in the reaction bond to create new compounds. This idea is held by several of the participants.

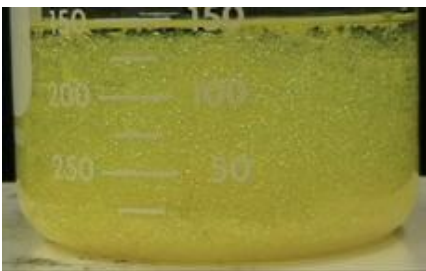


Figure 4. 38 Screen Capture of Lead (II) Iodide Precipitate

Ben (P5) explained his ideas about the creation of new molecules and his uncertainty regarding the role of water in a precipitation reaction in the following equation (Figure 4.39) and excerpt:



Figure 4. 39 Ben's Precipitation of Lead (II) Iodide Equation

P5: Um, (*pauses*). As I can recall this might be close to the recombination formula. I wasn't sure whether there, and I am still not sure, whether there was water in the solution or not. But actually I don't think it was in water. Both of these were aqueous solutions. So either the potassium iodide was in the beaker first and then the lead nitrate was added to it or vice versa. What I have represented, once again, this is perhaps the beginning of the reaction and this would be the final result of the reaction. This is representing as best as I could come up with the potassium iodide and the lead nitrate yielding the two new molecules, two compounds, which would come out of it.

Ben refers to this precipitation reaction as a “recombination formula”, which the researcher assumes he meant two new compounds were formed through a rearrangement of ions in the reactants. Ben also demonstrated an apparent lack of understanding of the term aqueous, when he says he does not think the solution was in water and later referred the same solution as aqueous. With the exception of William (P12), no other participant in this

category treated the solid lead (II) iodide precipitate differently than the aqueous potassium nitrate.

Equations from three participants were included in the water as reactant category. Participants in this category continue to demonstrate a mental model in which the role of water in solutions is one in which water bonds to other compounds. Wendy's (P6) equation (Figure 4.40) and explanation follow as an example of this category:

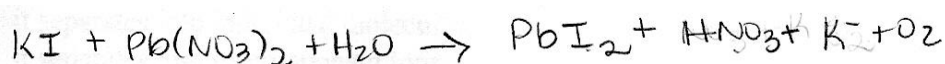


Figure 4. 40 Wendy's Precipitation of Lead (II) Iodide Equation

P6: In thinking that I would not have individual ions. I combined my component ions together to get the lead iodide. Then I said that the, um, the lead in the iodide would combine to give me the solid lead iodide. Then I combined my hydrogen with my nitrate. I left my potassium alone as an individual molecule.

Three participants included only the solid in the products of the equation without clearly explaining or addressing what happened to the spectator ions. Melissa's (P10) mental model of this reaction includes the idea that the potassium and nitrate ions combined, but later dissolve or disappear. It is not clear whether Melissa does not understand the conservation of matter, or if she does, she does not understand how to explain what happens to the potassium and nitrate ions. Her equation (Figure 4.41) and explanation follow:

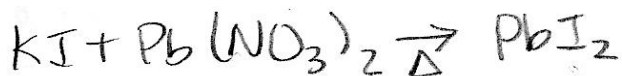


Figure 4. 41 Melissa's Precipitation of Lead (II) Iodide Equation

P10: Okay. This is the iodine and the nitrate mixed with heat. Then it becomes iodide, solid lead iodide.

R: What are the, what do you think is combining again?

P10: The potassium iodide and the lead nitrate.
 R: Okay. So what actually is combining to create that lead iodide?
 P10: Um, maybe the potassium and the nitrate.
 R: So you think the potassium and the nitrate?
 P10: I think they combine but somehow they disappear. They combine and maybe dissolve somewhere else or disappear or something. All that is left after they combine is the potassium and the iodine (pointing to PbI_2 in equation).
 R: Do you mean the lead?
 P10: Yeah, I'm sorry, the lead and iodide.

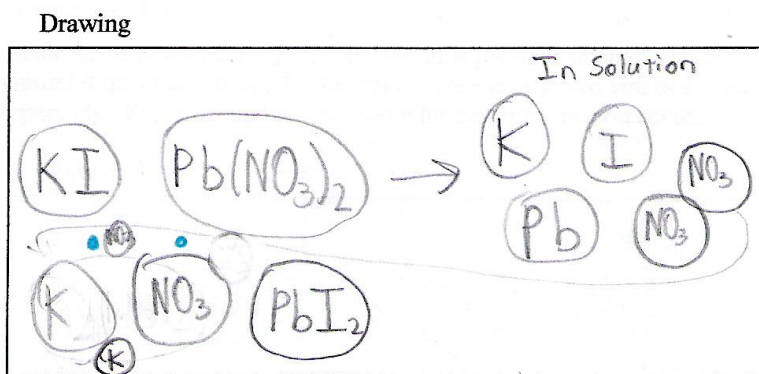
As with the dissolution videos, participants were asked to draw an image representing the phenomenon of aqueous potassium iodide and aqueous lead (II) nitrate combining to form solid lead (II) iodide. The pictures were sorted into four thematic categories. The first three thematic categories were the same as those used for the equations: 1) double displacement, 2) water as reactant, 3) solid as product, and 4) influence of macroscopic properties. The fourth category, influence of macroscopic properties, includes drawings and explanations that are dependent upon the macroscopic properties of the reaction, such as color or layers. Table 4.25 includes the number of responses in each category.

Table 4.25 Thematic Categories of Participants' Drawings of the Precipitation of Lead (II) Iodide

<i>Thematic Category</i>	<i>Number of Responses</i>
Double displacement	5
Water as reactant	3
Solid as product	3
Influence of macroscopic properties	4

Note. The number of responses does not total 12 since the responses could be placed in multiple categories.

Examples of the various categories of drawings are illustrated in the following interview excerpts. In the following drawing (Figure 4.42) and excerpt, William (P12) illustrates his mental model of a precipitation reaction. William's mental model is the closest to the conceptual model of the process of precipitation shown by any of the participants.



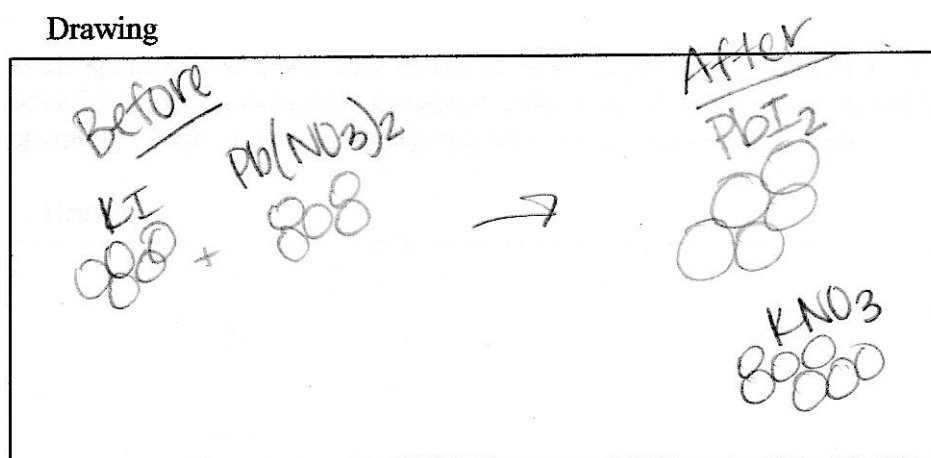
Explanation:

Potassium iodide and aqueous lead (II) nitrate undergo a double displacement reaction and form solid lead (II) iodide. Potassium and nitrate remain ions in the solution.

Figure 4. 42 William's Precipitation of Lead (II) Iodide Drawing

P12: In my drawing, these (*points to circles labeled KI and Pb(NO₃)₂ in drawing*) are just representing our molecules in a very simplistic illustration. They initially break apart in the solution. They reform. Lead II iodide forms leaving potassium and nitrate in solution. These two would actually have the, excuse me, the potassium would have a +1 charge. I inadvertently wrote two here. They actually should have two separate molecules. NO₃s should not be together. (*makes changes on paper – changes +2 to +1 and separates NO₃'s*) They would each have a -1 charge. I am just going to quickly just draw a valence electron.

Samantha (P3) in her drawing (Figure 4.43) and explanation illustrates the two reactants as combining to form two new products, in which the lead (II) iodide is more compact since it is a solid. The idea of solids being more compacted than liquids was expressed by two participants. Although Samantha writes in her explanation about the compact state of the solid, her drawing does not reflect this idea. As seen in Samantha's earlier excerpt on her equation for this precipitation reaction, her mental model is influenced by the macroscopic properties which she observed in the video. See Figure 4.38 for a screen capture of the video with a top layer and floating particles.



Explanation:

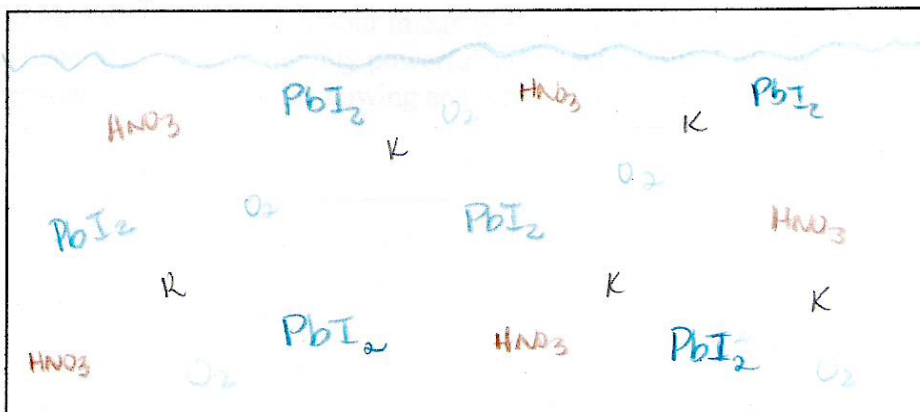
The KI and the $Pb(NO_3)_2$ react to create the PbI_2 which is in a more compact state.

Figure 4. 43 Samantha's Precipitation of Lead (II) Iodide Drawing

P3: Okay, so this (*labels before*) is before and this (*labels after*) is after. So before they're they're the compounds that are separated and then we add them and they all come together to form the thick layer at the top.

- R: Okay, is there something else in your equation that needs to be in your drawing?
- P3: Yes (*begins adding to drawing*) This would be the potassium nitrate.
- R: Okay, here (*pointing to written explanation*) I notice that you say it's creating the PbI_2 which is in a more compact state...what do you mean by that when you say it's compact?
- P3: When I, solid layer when it was all clumped together that's what I figured
- R: Is that layer...do you mind us looking at the video and lets see which layer you're talking about there to make sure I understand you clearly (*opens up video*)...is it towards the end?
- P3: Yeah, I think it's the top layer that I'm talking about but...
- R: (*stops video on clip near end*) okay, so we're looking here
- P3: it's this right there and then you have like the little space which I figured was the...
- R: okay, so point to the, what do you think is the lead two iodide here
- P3: This (*points to thin layer of lead iodide at top of water line in beaker*) at the top.
- R: Okay, are you pointing...
- P3: This this really thin layer right there
- R: not the clear layer?
- P3: Right
- R: And then you're saying this...
- P3: This (*pointing to where lead two iodide crystals are settling towards bottom*) would be the potassium nitrate

Wendy's (P6) drawing (Figure 4.44) and explanation are an example of the second category in which water is viewed as a reactant that bonds with other particles to create new compounds. Her explanation also illustrates the use of macroscopic properties to explain the chemical phenomenon at hand.



Explanation:

When the two aqueous solutions of KI is combined with $Pb(NO_3)_2$, the two molecules lead & iodide have an attraction so they bond together to form PbI_2 .

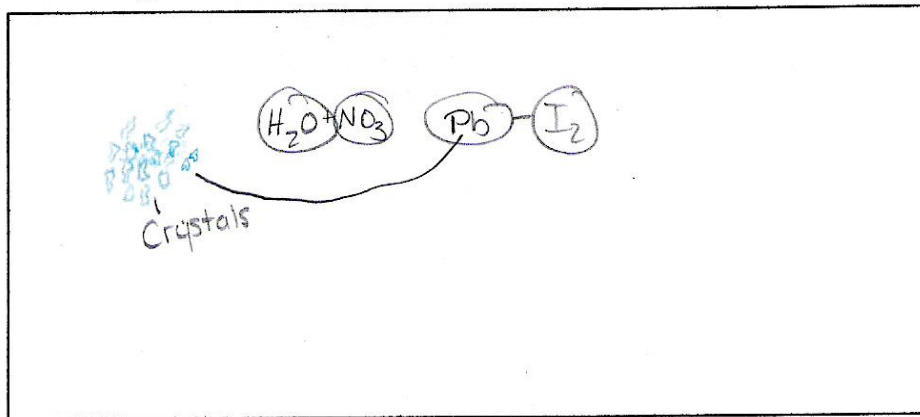
Figure 4. 44 Wendy's Precipitation of Lead (II) Iodide Drawing

- P6: Um, just like I have done in my previous two. It is that I had my component ions together and I had my potassium by itself along with the oxygen. *(mumbles quietly to self)* which is supposed to be actually hydrogen
- R: You asked me when we were watching the video. You wanted to know with this one if the little silver pieces would be solid lead. What is your thinking about that?
- P6: Well in knowing that lead is silver and I did not if the combination of the lead and the iodide would cause it to create the silver flecks that I saw in the video.
- R: I am going to have you, just for clarification, I am going to pull that video up and let you point and make sure that I understand what you are referring to when you call it a fleck. *(opens up video)*
- P6: What appears to be the solid objects in there. In the last frame it appeared to have a shiny appearance to it or silver appearance to it. *(points to lead (II) iodide crystals)*

Teresa's (P8) drawing (Figure 4.45) and explanation are another example of the water as reactant category, but also illustrates inaccuracies in her mental model regarding what

makes a solution aqueous. It is also an example of the third category of solid as product and the fourth category, influence of macroscopic properties.

Drawing



Explanation: This would occur due to the fact of bond joining of molecules of lead and iodide along with Nitrate

Figure 4. 45 Teresa's Precipitation of Lead (II) Iodide Drawing

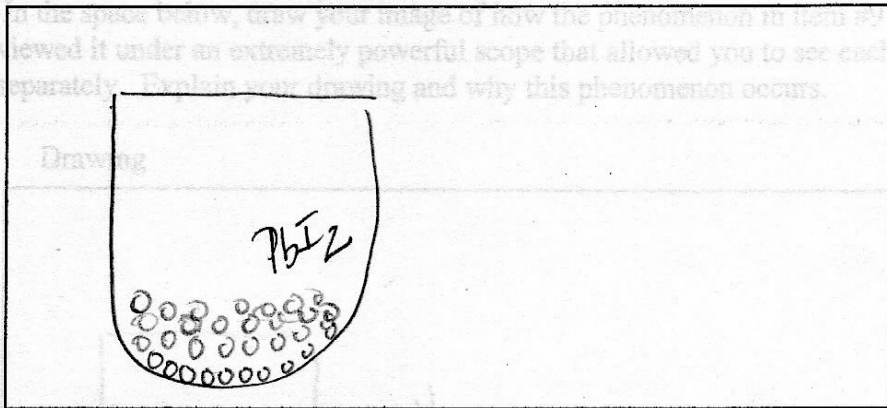
- R: Could you maybe try to draw what you think is going on there now?
- P8: Umhuh. So it would be the water, lead, and the iodide together. So it would be (*mumbles to self and adds to drawing – can't see paper on camera*). The nitrate would be bonded to the water. Like that.
- R: So just a minute ago you were saying that when you thought about this type of equation you thought of a solid being made in an aqueous solution. Of what you just drew which one is the solid?
- P8: With the Pb and the I₂.
- R: Okay. So what makes it the aqueous solution?
- P8: The water and the nitrate.
- R: The nitrate. Okay. So what would that solid actually look like in the video? Do you have any ideas when you look at the video what was the solid? Do you want to look at that video again real quick to refer back to it?
- P8: Yes
- R: (*shows video*)
- P8: Crystals. That's what it is.
- R: So the solid would be those crystals.
- P8: Umhuh.
- R: So they would be.....Is that what the dots there?
- P8: These would be the crystals.

R: Okay. Would you write crystals down so I will remember that is what you were referring to.

P8: (*writes "crystals" on drawing*)

Susan's (P2) drawing (Figure 4.46) and explanation illustrate the strength and consistency of her mental model as previously seen in regards to how solids dissolve. In the following excerpt, Susan continues to represent the dissolving of solids as a "cycle" consisting of solid particles connected to water particles. Building upon that idea, Susan explained how the precipitate remained in the "cycle", but the other compounds, including water, are no longer a part of the "cycle".

Drawing



Explanation: The aqueous solutions would be solid particles and the volume would decrease in the beaker.

Explanation:

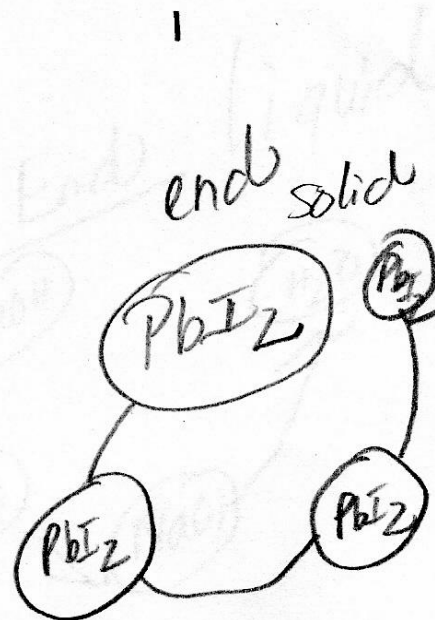
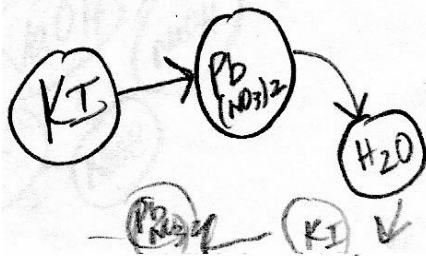
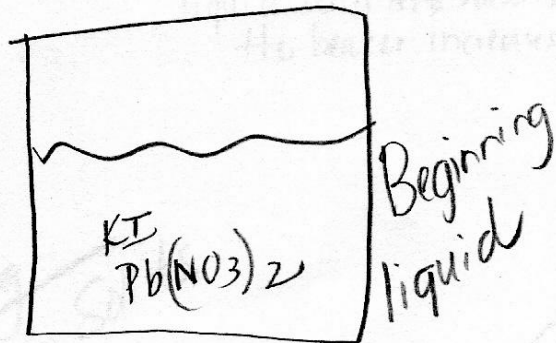
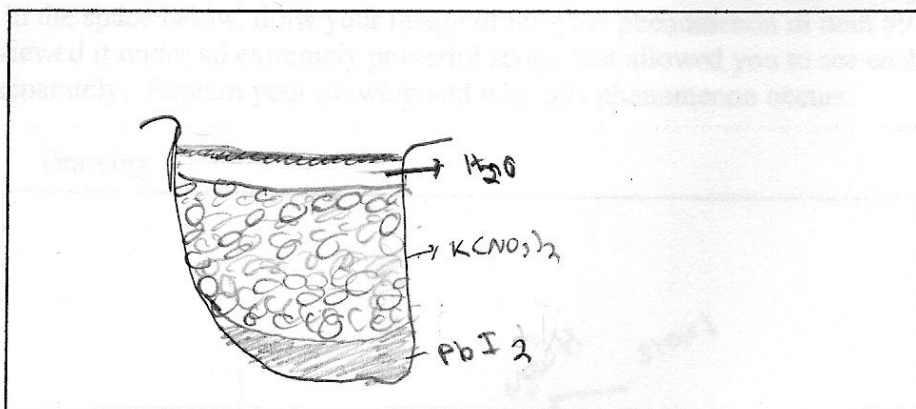


Figure 4. 46 Susan's Precipitation of Lead (II) Iodide Drawing

- R: Okay, umm so let's look at this one you're drawing, you have little circles present in the beaker...what do those circles represent?
- P2: These here would be what it formed (*pointing to circles in beaker in original drawing*), so this would be the solid lead, solid lead iodine
- R: Okay, could you maybe label that to make sure I understand that later on
- P2: Okay
- R: And let's try to think through this one again that if we watched that whole video with that powerful microscope that allowed you to see what was going on.
- P2: okay, then we might would have a beaker, I might would say we have a beaker and in the beaker we would have these solutions and you would have the potassium iodine solution in one beaker and also the lead nitrate ...okay and then, but then this would be the beginning and these would all be liquid
- R: What would that look like? Kind of like how you represented it before...could you try to show for me, you know, in the previous ones you've kind of drawn circles and things
- P2: Okay
- R: What would you think that would look like? But again, if we're looking at this beaker with a real powerful microscope what would you think it would look like?
- P2: Okay, then you might would have this molecule attached to this one here ...and....then you would also have the water molecule here and this would kind of be a cycle...and then in the end you would just have this one molecule kind of floating everywhere . So you would have all these molecules, this same molecule, just multiple, many of them
- R: Okay
- P2: Okay,
- R: Okay, I just want to clarify...you just said this would be like a cycle on this step...
- P2: Well yeah,
- R: I just want to be sure I know what you mean
- P2: Well, it would kind of be like not really a cycle but just connected like all these molecules connected together, you know what I mean, like different, there may be another KI here and another lead nitrate there
- R: So kind of connected is what you mean
- P2: Yeah

Jasmine's interview excerpt is an example of the final category based on macroscopic observations. As previously discussed, Jasmine struggled to make sense of what she observed with her equation and her drawing (Figure 4.47).

Drawing



Explanation: Under an extremely powerful scope the image would show the mixture in diff. parts based on the density of the each solution.

Figure 4. 47 Jasmine's Precipitation of Lead (II) Iodide Drawing

- P9: (laughs) Um, well they said, well honestly they gave me one of the products. I was like okay potassium iodide, so I put that there. I used what was left and combined the potassium with the nitrate. Then I tried to balance it a little bit. I was like, got a little nervous, I was just going to leave it there. And, um, so I realized that like they gave me one of the products so I just kind of okay so potassium nitrate would be the other product. So I realized in the video that it showed three different...when it was dissolved you can visualize, actually see, the separation in the different compounds. Since it showed three different ones, this equation probably should be broken down again.
- R: I am going to look at the video. I want you to point to me. I am going to say for the camera what you are pointing to. So that I understand when you are saying that you see three different. I want to make sure that I understand what you are calling three different. So if we look at the lead two iodide and go to the end. Would it be right at the very end that I see the three?
- P9: Yes
- R: Okay. So if we looked at this, what are you referring to as your three?
- P9: It would be the bottom layer, which is...
- R: So there is a bottom layer
- P9: which I am assuming is the most dense. Then you have kind of like a cloudy layer at the top that is different. It has some separation. It looked like it may be water that is right there.
- R: Okay.

P9: So it looks like maybe actually four different.

R: Essentially you are saying one layer is stopping at the first graduation mark.

P9: Umhuh

R: Then you kind of have a second layer that is from the first graduation mark on the beaker up to, slightly above, that would have been 125.

P9: Umhuh

R: Okay. Then you are saying this third layer would be like a layer of water. The fourth layer, you are now saying, is kind of right at the top of that water that looks cloudy. That is right around the 150 graduation mark. Is that correct? Is that what you are saying?

P9: Yes. That is what I am saying.

R: Okay. Alright. So talk to me about what you think those layers are and let's try to label them on your drawing what you think they may be?

P9: The second layer from the top is water.

R: Okay.

P9: Potassium nitrate, I think maybe the third layer. So I am looking at the periodic table right now to look at the molecular mass of the elements.

R: Umhuh. So what is your reasoning? What do you want to do with the molecular mass?

P9: I am seeing which one is bigger because I know that the weight of each element would go into play where its location would be in the mixture.

R: Okay.

P9: So I am looking at it trying to figure out, Okay, how big is potassium 39 (*looking at periodic table*), iodine, lead. I think potassium iodide would be at the bottom because it has the most.

R: Potassium iodide?

P9: Not potassium. Lead.

R: Umhuh.

P9: Would be at the bottom.

R: Your reasoning again for thinking that this is the bottom.

P9: Because it has combined, its molecular weight would be the largest (*labels layers on drawing*).

R: Okay.

P9: In looking at this I would think that Okay hold on I said it was four layers and I only have really two products to me but there is four layers. I am saying that they are separated. So to me I would be like Okay maybe my chemical equation is wrong because I have four different layers that I can visually see. It may be even more layers if we look under the microscope. So I would have just assumed to go like okay well let me just erase and separate the compounds and the product and maybe just put the lowest one which would when looking at the chart would be potassium maybe by itself.

R: So do you want to change your equation?

- P9: I don't want to change it but I would be kind of torn between that. Like really not knowing like okay I forgot how to break down the chemical equation. I would be like. That would make sense in my head to say Okay well let me just change this, change the equation around so it could look like the picture.
- R: Okay. That is what I am interested in. What makes sense to you? So why don't we do this, if you will maybe draw a line under that and what makes sense to you. I would like for you to write that.
- P9: Um. *(pauses a long time while thinking and writing new products for equation)* Potassium nitrate and then I would say okay...um...potassium iodide...um...maybe separate the iodine and the lead. I would think that maybe since the water was used in the beginning that it separated some so you will have... *(pauses a few seconds)* Now I am thinking maybe even in the picture as it shows it may be like a little shadow. Well, not like a shadow but...I know....
- R: What were you saying that it might be like a shadow?
- P9: Like a little shadow here.
- R: So that layer that we had previously, you had identified as possibly the water, you are thinking that might now be like a shadow but you are not sure if it is really a shadow.
- P9: Right.
- R: Okay.
- P9: And again it could be the same.
- R: Could be the same as what?
- P9: The same, um, solution but it just didn't have time to dissolve. Well, I am actually not sure because looking at the equation and looking at what I see is like the equation is wrong but what I see is like it is telling me that okay so maybe the compound broke down instead of four different layers. You know one of the elements separated and went by itself but the equation does not say that. It should both make sense to come together. I am not seeing that, so I am kind of stumped here looking at it like. I don't know how to explain it. What I see and then the chemistry behind it is not like equaling up. It is not making sense.
- R: So let's forget about the equation for a minute. Talk to me about what in your mind you think is happening when we mix those two solutions together. So don't worry about trying to match it to the equation. You know that needs to happen but you are kind of tied up on that right now. Just talk to me about what you think is going on? What makes sense to you that is happening if we were looking at it with that really, really powerful scope that you could kind of see.
- P9: In my mind I will see that like where the molecules...when compounds when they came together that they separated and formed other compounds. Even the water that was in one of the compounds may have come out a little bit so that you can see that through the microscope.

- R: What do you mean when you say one of those molecules may have come out? What do you mean exactly by that when you say came out?
- P9: It may have separated, not came out, but may have separated again. When you added it to...it caused it to form back into its natural state of maybe water.
- R: So you think that the compounds are changing?
- P9: I know that they are changing. You put it together...kind of like Kool-Aid, water, and sugar. You put it together. It looks like a homogeneous solution but it is not. I can tell this looks like a heterogeneous.

Jasmine continues to be the only participant who consciously attempted to reconcile differences in ideas using the three levels of representation: macroscopic, microscopic, and symbolic.

Precipitation of Iron (III) Hydroxide

Participants were asked to write an equation that represented the precipitation of iron (III) hydroxide from the reaction of aqueous sodium hydroxide and aqueous iron (III) nitrate. The resulting equations were sorted into three thematic categories: 1) double displacement, 2) water as reactant, and 3) solid as only product. The categories were identical to the categories used for the precipitation of lead (II) iodide. Table 4.26 includes the number of responses in each category along with examples of student's equations. The precipitation of iron (III) hydroxide is the only video where none of the participants indicated that water bonded with other compounds in the reaction. It is assumed that the presence of the hydroxide polyatomic ion is linked to this anomaly. Examples of responses in category #1 and #3 are illustrated in the following interview excerpts.

Three quarters of the equations were categorized as double displacement reactions. As seen with the precipitation of lead (II) iodide, William (P12) was the only participant who

accurately represented the existence of spectator ions in his equation. His equation (Figure 4.47) and explanation follow:



Figure 4. 48 William's Precipitation of Iron (III) Hydroxide Equation

P12: Okay. In this case we have sodium hydroxide. It is combining with our iron three nitrate. It forms a precipitate of our iron three hydroxide. Leaving our sodium and our NO_3 suspended in solution. They would not form a precipitate.

Most of the participants whose responses were included in the double displacement category indicated that they believed the spectator ions, Na^+ and NO_3^- , bonded due to their opposite charges. In the following equation (Figure 4.49) and exchange, Kim (P7) discusses the attraction between the sodium and nitrate ions:

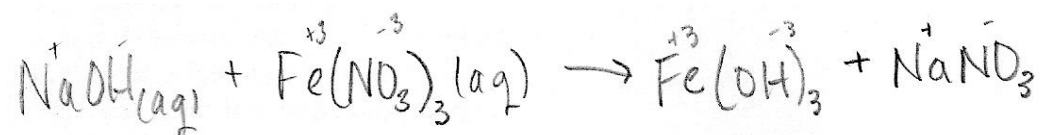


Figure 4. 49 Kim's Precipitation of Iron (III) Hydroxide Equation

P7: So we have the NaOH, that is aqueous, as well as the iron, no, nitrate, sorry, aqueous as well. These will each be...um... separate initially, OK? Put into the water, they disperse, and as a result they form bonds or attractive forces with opposite constituents. So you have got Fe here and that is positive three. This would bond with three of the hydroxides, so you would have positive three iron and then negative three hydroxides. You would need three to make that because they are normally negative with just one. Then you have the sodium and nitrate coming together. It is positive and negative ions.

Table 4.26 Thematic Categories of Participants' Equations Representing Precipitation of Iron (III) Hydroxide

<i>Thematic Category</i>	<i>Number of Responses</i>	<i>Examples</i>
Double displacement	9	$3\text{NaOH} + \text{Fe}(\text{NO}_3)_3 \rightarrow \text{Fe}(\text{OH})_3 + 3\text{Na}^+ + 3\text{NO}_3^-$ <p>Equation that represents this chemical phenomenon.</p> $3\text{NaOH} + \text{Fe}(\text{NO}_3)_3 \rightarrow \text{Fe}(\text{OH})_3 + 3\text{Na}(\text{NO}_3)$
Water as reactant	0	N/A
Solid as only product	3	$\text{NaOH} + \text{Fe}(\text{NO}_3)_3 \rightarrow \text{Fe}(\text{OH})_3$

Jasmine (P9) demonstrates a similar mental model in which the spectator ions are attracted and are together in the following equation (Figure 4.50) and excerpt:



Figure 4. 50 Jasmine's Precipitation of Iron (III) Hydroxide Equation

- R: It makes a new compound? That's what that color change says to you. Is it makes a new compound. Okay. You are just not clear on what that new compound would be? Okay. Alright. Let's look at the final video here. This is where you mixed the sodium hydroxide with the iron III nitrate to form the iron III hydroxide. Talk to me about how you got your equation here.
- P9: One thing since it gave a product I was like okay. So it formed iron hydroxide. I just said it formed sodium nitrate.
- R: Okay. You have a plus mark, it looks like, beside that sodium. Are you keeping those separate? What did that plus mark mean? Is that a plus mark?
- P9: I am not sure (*erases mark from equation*)
- R: So do you think that sodium and the nitrate are together.
- P9: Yes.
- R: Is that the way you have it written?
- P9: Yes. I think it came together. Umhuh.

One quarter of the participant's individual equations were included in the solid as only product category. Amanda's (P4) explanation illustrates how participants used the information provided on the questionnaire as clues in developing responses. Her equation (Figure 4.51) and transcript excerpt follow:

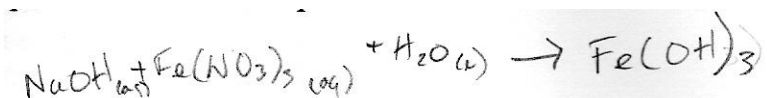


Figure 4. 51 Amanda's Precipitation of Iron (III) Hydroxide Equation

- R: We may come back and revisit that question. I'll give you a little time to think about that. All right so with our final video, we were mixing our sodium hydroxide with our iron three nitrate to produce the iron III hydroxide so how did you come up with this equation?

P4: Umm, like the other one before I really thought the answer was in the question and the formulas right there so I put it all together.

As with the dissolution videos, participants were asked to draw an image representing the phenomenon of aqueous potassium iodide and aqueous lead (II) nitrate combining to form solid lead (II) iodide. The pictures were sorted into four thematic categories. The first three thematic categories were the same as those used for the equations: 1) double displacement, 2) water as reactant, and 3) solid as product. The fourth category, influence of macroscopic properties, includes drawings and explanations that are dependent upon the macroscopic properties of the reaction, such as color or layers. Table 4.27 includes the number of responses in each category.

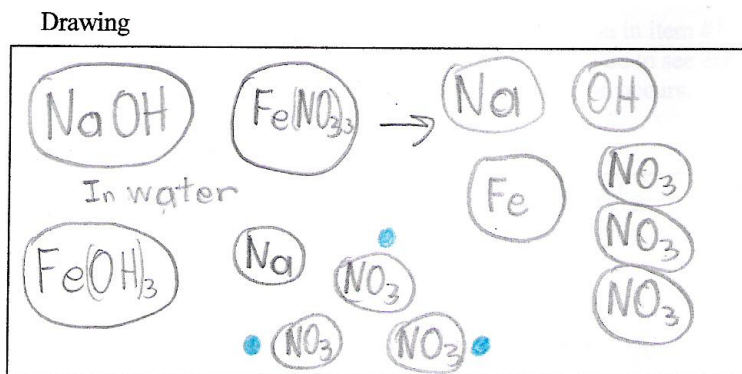
Table 4.27 Thematic Categories of Participants' Drawings of the Precipitation of Iron (III) Hydroxide

<i>Thematic Category</i>	<i>Number of Responses</i>
Double displacement	8
Water as reactant	1
Solid as product	2
Influence of macroscopic properties	4

Note. The number of responses does not total 12 since the responses could be placed in multiple categories.

Two thirds of the participant's individual drawings were classified in the double displacement category. Once again, William (P12) is the only participant whose mental

model is accurate and is consistent with previous responses. His drawing (Figure 4.52) and explanation follow:

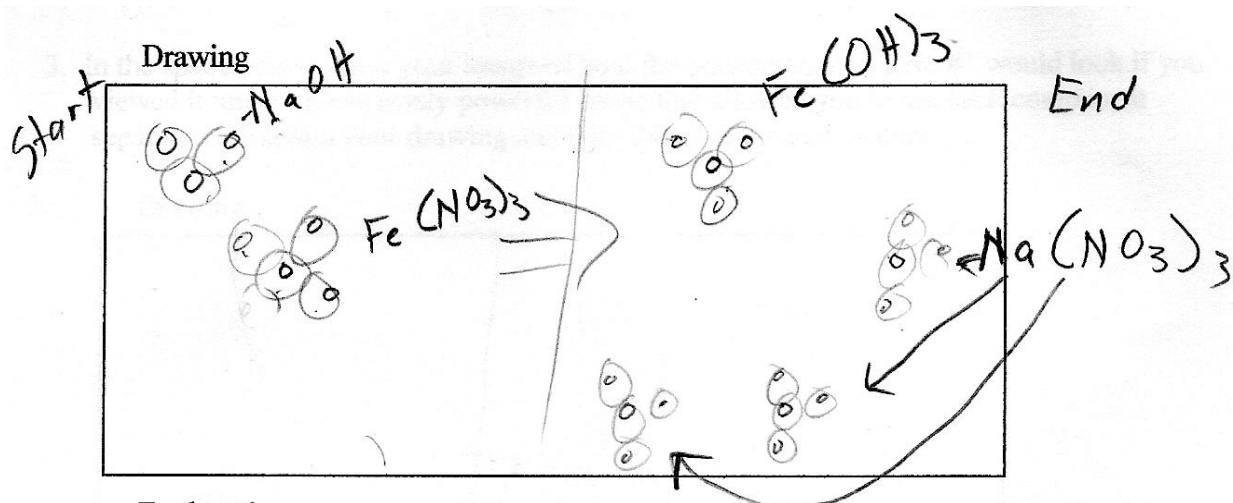


NaOH and $\text{Fe}(\text{NO}_3)_3$ bonds break and Fe and $(\text{OH})_3$ form a precipitate while Na and NO_3 remain in solution.

Figure 4. 52 William's Precipitation of Iron (III) Hydroxide Drawing

P12: Okay. In this case we have sodium hydroxide. It is combining with our iron three nitrate. It forms a precipitate of our iron three hydroxide. Leaving our sodium and our NO_3 suspended in solution. They would not form a precipitate.

Ben's (P5) drawing and explanation were also included in the double displacement category. During the interview, Ben explained his understanding of the word precipitate by comparing it to rain. His drawing (Figure 4.53) and an excerpt of his interview follows:



Explanation:

2 when combined ~~to~~ break original bonds to form better bonds yielding 2 new compounds.

Appears to be a precipitation reaction
I assume the Fe(OH)₃ is the precipitate

Figure 4. 53 Ben's Precipitation of Iron (III) Hydroxide Drawing

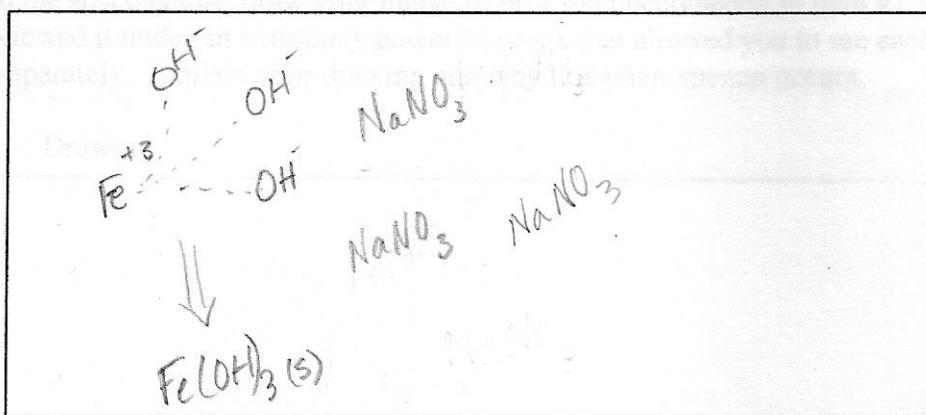
- R: If you think you need to change it that is fine.
- P5: I drew one extra molecule here didn't I?
- R: Okay.
- P5: That would be the iron and this would be the NO₃. This would not matter. One sodium, one oxygen, and one hydrogen here and a recombination. This is our FeO₃ and OH (*gets quiet as he is working it out*). These are all something which could have been this compound.
- R: Okay.
- P5: This was definitely the most dramatic of the three reactions. It also occurred to me that while I was watching that that it was a precipitation event which occurred.
- R: Umhuh
- P5: I am assuming since iron would be the heavier substance it would be the precipitant. That is what dropped to the bottom of the beaker.

- R: So what do you remember? You were saying it appears to be precipitation reaction. What does that term mean to you?
- P5: I think literally it means something falling. In precipitation in an atmospheric event is rain or any sort of water which falls to the sky. That term has been also applied to chemistry if I remember correctly. In either event there is a recombination of molecules where something has an added mass, I suppose. Would naturally gravitate lower, have higher gravity so it would sink to the bottom of the solution as compared to lighter.

Kim's (P7) mental model of this reaction is different than the other participants.

Although her equation and drawing are categorized as double displacement, her explanation for this reaction is different than her explanation for the previous precipitation reaction. In her drawing (Figure 4.54) and the following excerpt, notice how she explained a dynamic situation in which the spectator ions, Na^+ and NO_3^- , bond, break apart, and bond again.

Drawing



Explanation:

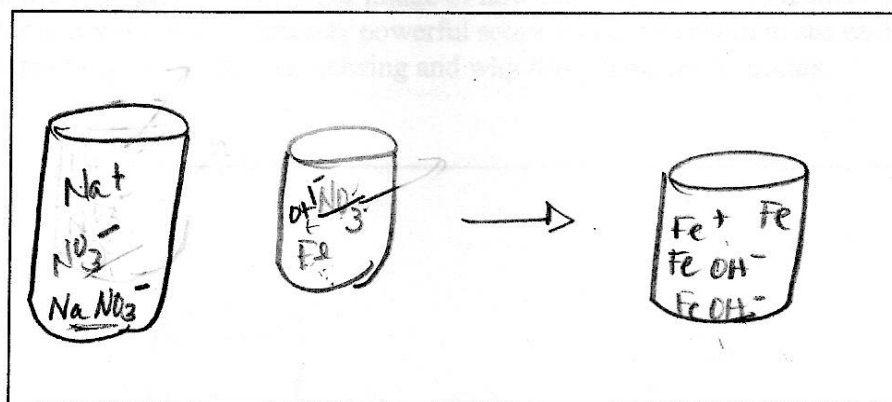
Fe^{+3} and 3 OH^- (bond) combine to form solid $\text{Fe}(\text{OH})_3$
 all the while NaNO_3 has bonded and stay in aqueous form.

Figure 4. 54 Kim's Precipitation of Iron (III) Hydroxide Drawing

- R: Okay. So show me here in your drawing. It looks like maybe you represent these two differently (*points to Fe—3 OH's on top and Fe(OH)₃ on bottom*). Is there a reason why?
- P7: Um, no, not really. Just have Fe and you know it needs three of those negative hydroxides. It comes together. As a result, you have this solid here (*points to Fe(OH)₃ at bottom*). In the NaO₃ I did not make them solid because they don't become solid. They stay in solution. I just left them together because that is the way I did it.
- R: So if they stay in solution what would they look like if you were trying to draw that?
- P7: If they stayed in solution?
- R: You said they stay in solution.
- P7: Umhuh
- R: You said you did not do that you just left them together. What do you think they look like since you are saying they stay in solution.
- P7: I would say it would be just a whole bunch of Na and NO₃s together. They are most likely dynamic so they are not bonding and staying together. They probably would bond, come apart, and then rebond again with a different group.

In Renee's (P11) drawing (Figure 4.55) and explanation, she revealed how her mental model was changing. Renee originally indicated that the spectator ions "evaporated" out of the solution. During the interview, she expresses discontent with this idea. Renee also explains the influence of macroscopic properties on her identification of the precipitate in the video, combined with her knowledge of rust.

Drawing



Explanation:

The Na and NO_3 join to form a molecule.
~~The Na and NO_3 evaporates out of the solution.~~ The Fe and OH join since they are opp. charges forming an oxidizing agent rust.

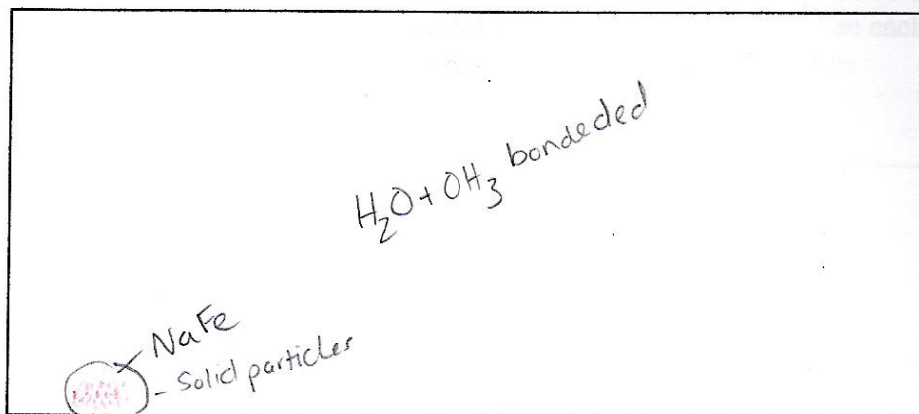
Figure 4. 55 Renee's Precipitation of Iron (III) Hydroxide Drawing

- R: Alright. So can you talk through your drawing for me here and what the arrows mean?
- P11: Umm, the iron, not the iron, the sodium and the oxide would evaporate out of the solution (*pointing to arrows pointing out of first beaker in drawing*). Then the iron and the hydroxide would join since they are opposite charges.
- R: Okay. You pointed to that (*points to NO_3 in the second beaker of drawing*) and called it hydroxide but that NO_3 is what?
- P11: It is nitrate. Sorry.
- R: So say it again what you think is going on there.
- P11: That's not right. That is supposed to be OH .
- R: If you just want to mark through it and then...

- P11: This is OH and this is supposed to be NO₃ (*marks corrections on first and second beakers in drawing*).
- R: Okay.
- P11: Negative. Okay.
- R: So arrows pointing out mean?
- P11: evaporating...
- R: ...that it is evaporating.
- P11: Yeah, evaporating.
- R: So do you want, since you changed this from NO₃ to OH negative, do you want that arrow there (*pointing to arrow coming out of second beaker*)?
- P11: No. That is only supposed to go here (*erases arrow coming out of second beaker*).
- R: Okay.
- P11: So. Yeah. That is not right either. Because it is out of here so it can't evaporate out. Can I change it?
- R: Umhuh.
- P11: (*changes drawing – erases first beaker and redraws beaker with Na's and NO₃'s*) So when they are separated into the water then they come together to form NaNO₃. This iron and the oxide are separated into the water (*points to second beaker in drawing*). Then they come together to form iron oxide. That is what I did over here (*points to third beaker in drawing*).
- R: Okay. Now on that video you noticed that there was kind of a dark substance. Do you have a clue what the identity of that dark substance was in the video?
- P11: That was iron oxide.
- R: How do you know that? What makes you think that?
- P11: Because of the color.
- R: What about the color?
- P11: It was dark brown.
- R: So why would you think dark brown would be the iron?
- P11: Because the oxidation agent, OH, changes the color of iron and makes it rust and stuff. So that was the color of rust.

Teresa (P8) is the only participant who illustrates the belief that water bonds to a component in the reaction. Though this idea was described by multiple participants during the dissolution videos, it is not as common in the precipitation reactions. Teresa also believes that the sodium and iron ions bond to form the solid. Teresa's drawing (Figure 4.56) and explanation during the interview follows:

Drawing



Explanation: A solid metal is formed of sodium iron hydroxide.

Figure 4. 56 Teresa's Precipitation of Iron (III) Hydroxide Drawing

- P8: Um, the two solids would join and the hydroxides would join.
R: I am sorry. Say that again?
P8: The hydroxides would join. So this would be like the sodium and the iron together would make this solid particle.
R: What happens to everything else that is in there? Is that the only thing that is in there?
P8: Um, no it is the hydroxides.
R: So what would it possibly look like?
P8: Um, just, it would be in with the water.
R: What do you mean in with the water?
P8: It would be like a liquid...aqueous
R: Could you draw kind of...Do you think that it is bonded? In some cases you have said it bonds to the water. Others you haven't. So which one do you think it would do?
P8: It would be bonded to the water...okay let me put bonded (*adds label to drawing*)

Amanda (P4) is one of the two participants whose drawings were included in the solid as only product category. During her interview, Amanda again references her understanding about the structure of solids in saying that they are compact. Amanda's drawing (Figure 4.57) and interview excerpt follows:

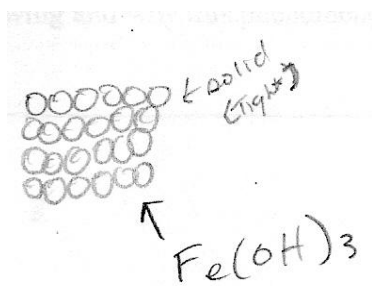
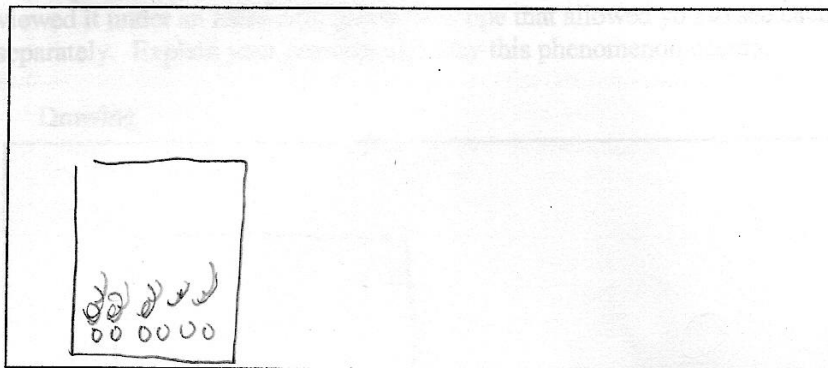


Figure 4. 57 Amanda's Precipitation of Iron (III) Hydroxide Drawing

- R: okay, umm, and if you'll talk through your drawing for sixteen ... does this represent the beginning, the middle, the end?
- P4: Umm, it represents the end
- R: okay, and so what have you drawn for me
- P4: Well this is the, umm, sodium, the solid iron three hydroxide (*adds label to drawing*) and when I think solid, I think tightly compacted so that's why they're all together like that
- R: okay, so like we did before is if we think about the two videos prior to this, your drawings for those kind of showed them breaking apart and so could you talk me through again in your mind what do you think happens when you take those two beakers where in one the sodium hydroxide you had it broken apart with the water, the other you have the iron three nitrate broken apart in the water, but when I mix these together could you kind of explain what you think is happening getting from that point to what you've shown me in this point (*points to drawing on item 16*)
- P4: Well, I'm going to go with pretty much the same answer I gave last time ...there's some ionic or covalent bonding is going one to where they're sharing or exchanging electrons to kind of jumble together.

One third of the participants referenced macroscopic properties in either their drawings or explanations of their drawings. While this has been seen frequently in other portions of the interviews, excerpts from Susan's (P2) and Jasmine's (P9) interviews are included to illustrate which macroscopic properties influenced their understanding of the precipitation reaction of iron (III) hydroxide. Figures 4.59 and 4.61 are a screen captures of the iron (III) hydroxide for reference in understanding Susan's and Jasmine's comments. An excerpt of Susan's (P2) interview explaining her drawing (Figure 4.58) follows:

Drawing



Explanation: In the beaker we would view particles of the $\text{Fe}(\text{OH})_3$ and possibly see it as a gas.

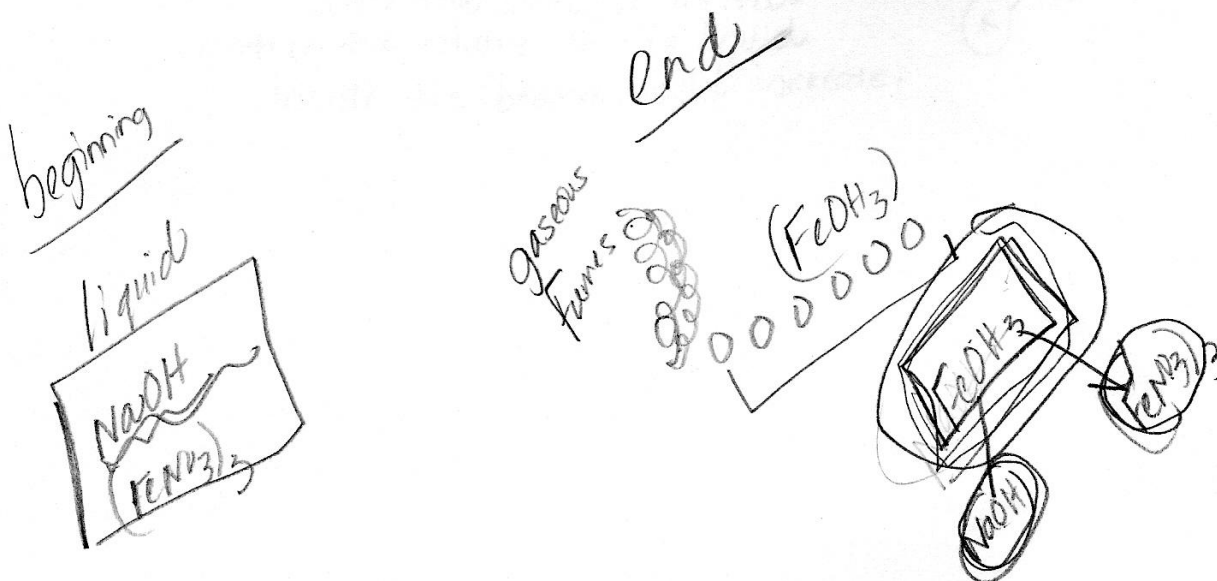


Figure 4. 58 Susan's Precipitation of Iron (III) Hydroxide Drawing

- P2: Well, in this one a little bit it looked like I could see like some fumes inside the beaker.
- R: Can we look at that and you point to me what you're referring to as the fumes?
- P2: Okay, that's why I've got those little things there (*pointing to squiggly lines in beaker above circles*)
(replays video)
- R: So what....

P2: It's kind of towards the end

R: Okay

P2: Right kind of here around this back part it look liked you could see like fumes that kind of look like gas...so when it gets there

R: gets there
(*video continues playing*)

P2: as it's settling can you see it looks like smoke back there (*points to left side of video*) to me that kind of looks like as it's settling to the bottom there's like fumes, like smoke

R: Is it the same thing that we're kind of seeing through here (*pointing to precipitate*)

P2: I don't know this one here I don't know if it's because it's the edge of the beaker, but I guess I could visualize it a lot more on that side

R: Okay, okay so if you'll label this drawing for me

P2: Okay

R: So I'll know what you mean and lets think again using that powerful microscope how you could maybe draw...

P2: Okay, well in the beginning, in the beginning it started out as a liquid solution, liquid in the beginning and as it, so I guess in the beginning all of them were liquid so you had the sodium in the beaker, you've got the sodium and it's a liquid and you've got this iron and it's a liquid, but then in the end you start seeing these particles forming on the bottom and then like these gassy fumes and I mean maybe that wasn't what that was but it surely did look like gassy fumes over here. Then you got these particles forming and these would be the particles ...this would be the this, so all these are this..see...okay I guess on the microscope if I looked at it in the microscope ...

R: If you would label what you're saying is the gassy fumes

P2: Okay, and I guess under the microscope you probably would see maybe this connected ... maybe not....maybe you would see the end product connected to this down here and then because it would take both of these to form this one and then you would just have multiples of these floating around under the microscope ...

R: So in the end product, in your drawing what you're saying is you would have sodium hydroxide present and iron three nitrate present and the iron three hydroxide present...so we'd see all of those at the end...is that what you're saying

P2: (*pause*) I guess so, because I guess I'm thinking in the end result you'd need to know what, how this formed or maybe this (*pointing to iron hydroxide*) would stand off a little more than these ...these would be kind of small and this one would kind of be big

R: So when you say it would stand off you, you're referring to the size?

P2: Yeah, yeah, because this is what is formed I would think this would might be a little bit bigger than actually what it was formed from

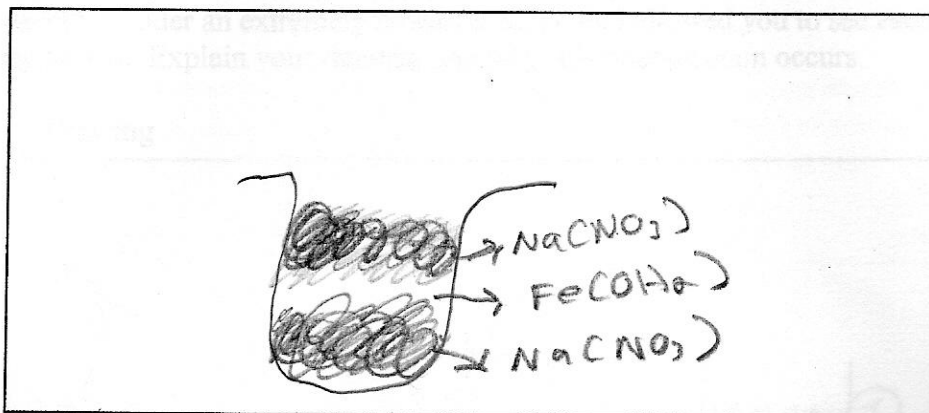
As seen in the previous exchange, Susan is very preoccupied with the appearance of what she referred to as “gassy fumes”. Those “gassy fumes” were actually the solid iron (III) hydroxide as it formed during the reaction.



Figure 4. 59 Screen Capture of Iron (III) Hydroxide Precipitate –Susan’s “gassy fumes”

In the following excerpt of Jasmine’s (P9) interview, she is influenced greatly by the appearance of layers in the video and incorporated layers into both her drawing (Figure 4.60) and explanation.

Drawing



Explanation: One can clearly see with the naked eye the chemical separation. The microscope will show the individual molecules in the mixture that are not formed together and may appear to be.

Figure 4. 60 Jasmine's Precipitation of Iron (III) Hydroxide Drawing

- R: Okay. Okay. So alright let's talk about our drawing here and talk to me about what the difference is. There is some scribbly lines, dots...
- P9: Dots
- R: and some darker scribbly lines. So talk to me about what you think those are?
- P9: (pauses) I am not sure which one would be which. From what I have seen it showed kind of like two different solutions.
- R: Let's look at that and let you point again and make sure I understand what you are referring too. (replays video) So if I look here at the end, what are you calling or kind of difference?
- P9: Ohh
- R: Does that help with the glare (adjusting computer screen)?
- P9: So it looks like it is the same, it just formed precipitate and one just fell down to the bottom. The other one is floating at the top. It is a different mixture in the middle that is separating the two precipitates, just like a cloud. A cloud has formed. (pauses) I am guessing, it is like, the precipitate-one would be sodium nitrate or iron hydroxide.
- R: So which one do you think is the precipitate?
- P9: (pauses) sodium nitrate
- R: Okay. So where do you think the iron hydroxide is?

- P9: The iron hydroxide, I think, is the kind of yellowish liquid in the middle.
 R: So just to clarify, you think the kind of yellowish liquid is the....
 P9: Iron hydroxide.
 R: Iron hydroxide. The kind of brownish stuff at the bottom...
 P9: Is the sodium nitrate.
 R: Is the sodium nitrate. You are calling the sodium nitrate, what was the word you used?
 P9: Precipitate.
 R: Just for clarification, how do you define the word precipitate? What does that word mean to you?
 P9: It is like, I guess like, a cloudy form.
 R: Cloudy. Okay. Alright. So let's look at your drawing here. Can you try to label what you just told me? Based on what you just said.
 P9: *(laughs)* Okay. Well, I am looking at this stuff right here would be the sodium nitrate *(right here)* and in its in liquid form *(labels layers in drawing)*.

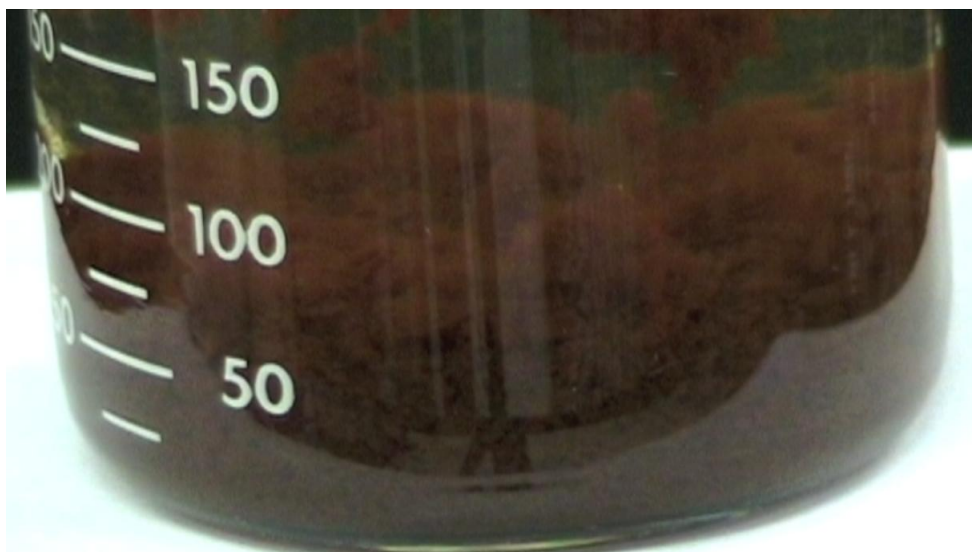


Figure 4. 61 Precipitation of Iron (III) Hydroxide Screen Capture – Jasmine's layers

Table 4.28 provides a summary view of the prevalence of thematic categories for participants' equations and drawings for the precipitation of the two ionic solids. The most prevalent category for participants' responses across the two ionic solids is double displacement. It should be noted that there was a 25% increase in this category for the iron

(III) hydroxide precipitate over the lead (II) iodide precipitate. The researcher assumes that the presence of the hydroxide polyatomic ion may have influenced this increase.

Table 4.28 Prevalence of Thematic Categories of Participants' Equations and Drawings of the Precipitation of Two Ionic Solids

<i>Thematic Category</i>	<i>Number of Responses</i>			
	PbI_2		$\text{Fe}(\text{OH})_3$	
	E	D	E	D
Double displacement	6	5	9	8
Water as reactant	3	3	0	1
Solid as product	3	3	3	2
Influence of macroscopic properties	0	4	0	4

Note. E= equation; D = drawing. The number of responses in each column does not total 12 since responses could be included in multiple categories.

Inconsistency of Participant's Mental Models of Precipitation Reactions

The previous two sections have presented data about participants' mental models regarding the precipitation of ionic solids. While analyzing the data, the researcher reviewed inconsistencies between individual participant's equations and drawings of the same chemical phenomenon. For both of the precipitation videos, the researcher classified each participant's level of consistency. If a participant's equation and drawing represented the same thing, it was labeled as complete consistency. Participants could also demonstrate partial consistency or no consistency between the two. Partial consistency means that a majority of the two representations match, but included minor differences such as the inclusion/exclusion of additional chemical species. An example of partial consistency would be one in which the participant included both products in the chemical equation, but did not include one of the products in the drawing or the explanation of the drawing. Table 4.29 illustrates the level of consistency demonstrated for the precipitation of each solid.

Table 4.29 Levels of Consistency Between Individual Participant's Responses for the Precipitation of Two Ionic Solids

<i>Levels of Consistency</i>	<i>Number of Participants</i>	
	PbI ₂	Fe(OH) ₃
Complete consistency between both representations	8	10
Partial consistency between both representations	4	2
No consistency between any representations	0	1

Summary

This study identified mental models held by 12 pre-service secondary science teachers on the topics of dissolution and precipitation reactions through the analyses of chemical equations, drawings, and interviews. In many cases, the mental models held by the pre-service science teachers contained misconceptions. For the topic of dissolution, participants' mental models included the following ideas: 1) change in state of the ionic solid, 2) creation of new compounds through the combination of water and the ionic solid, 3) separation of water into its components during dissolution, 4) separation of the ionic solid into incorrect or partially correct components, 5) separation of polyatomic ions in the ionic solid into components, and 6) separation of the ionic solid into the correct components. The first five ideas listed above represent common misconceptions about the process of dissolution.

For the topic of precipitation reactions, participant's mental models included the following ideas: 1) a precipitation reaction is a double displacement reaction, 2) water as reactant, and 3) the solid precipitate is the only product (without any indication of spectator

ions). While the first idea in which precipitation is viewed as a double displacement is not totally incorrect, most of the participants exhibiting this idea did not differentiate between the two products. The study also revealed that many of the participants' mental models are incomplete and include inconsistencies. Participants' mental models about dissolution exhibited more inconsistencies than their mental models regarding precipitation reactions.

Chapter 5
Conclusions

This study was conducted to identify pre-service science teachers' mental models about dissolution and precipitation reactions. Data collection included a written questionnaire in which participants answered multiple choice questions, provided chemical equations, and drew particulate level drawings after viewing videos of four ionic solids dissolving and two precipitation reactions. Each participant was interviewed to elicit additional information about each participant's mental model.

Dissolution

This study addressed a gap in the literature identified by Calik et al. (2007) in which very few studies have reported on pre-service teachers' understanding of solution chemistry. Calik et al. investigated the understanding of pre-service elementary teachers on the topic of solution chemistry. However, the researcher found no previously published studies reporting on the understanding of pre-service high school science teachers on the topics of dissolution and precipitation reactions. This study identified a group of twelve pre-service high school science teachers, all of which had completed a minimum of two semesters of introductory chemistry. The participants in this study were seeking a license to teach science at the high school level, and as such, are required to complete more science coursework than prospective elementary teachers. The researcher was curious to learn if and how the mental models of the participants in the current study compared to previously reported findings, in light of the additional college level science coursework completed by the participants.

Many of the pre-service science teachers in the current study exhibited the same or similar misconceptions as previously identified in middle school, high school, and introductory college chemistry students. Table 5.1 includes a summary of the frequency of

each category identified in participants' responses for the dissolution of the four ionic solids. The most prevalent thematic category regarding dissolution in the current study included separation of the ionic solids into incorrect or partially correct components. Data in this category include dissociating polyatomic ions and dissociating ionic solids into atoms or diatomic species. Participants in the current study exhibited ideas which resembles those cited in earlier studies (Ebenezer & Erickson, 1996; Lythcott, 1990; Nurrenbern & Pickering, 1987; Sawrey, 1990; Smith & Metz, 1996; Tien et al., 2007). While there was a high frequency (37) of participants understanding that the ionic solids separate into components, there almost as high a frequency (33) of participants who expressed the idea that the ionic solid bonds with the water to create a new chemical compound. This finding is similar to those previously reported in the literature (Abraham et al., 1994; Calyk et al., 2005; Ebenezer & Erickson, 1996; Ebenezer & Gaskell, 1995; Fensham & Fensham, 1987; Preito et al., 1989). Data from the current study also suggests a few pre-service science teachers do not make the distinction between the terms melting and dissolving, and use the two interchangeably. This common occurrence has been found in earlier research (Abraham et al., 1994; Muammer Calik, 2005; Muammer Calik & Ayas, 2005; Muammer Calik et al., 2007; Ebenezer & Erickson, 1996; Ebenezer & Gaskell, 1995; Preito et al., 1989).

Table 5.1 Summary of Participants' Responses by Thematic Category for the Dissolution of Four Ionic Solids

<i>Thematic Category</i>	<i>Number of Responses</i>				<i>Total</i>
	<i>KI</i>	<i>Pb(NO₃)₂</i>	<i>NaOH</i>	<i>Fe(NO₃)₃</i>	
Change in state	4	4	3	3	14
Creation of new compounds through the combination of the solid and water	11	7	7	8	33
Separation of water into its components	10	9	4	7	30
Separation of solid into incorrect or partially correct components	5	12	11	9	37
Separation of polyatomic ions into components	N/A	1	8	0	9
Separation of solid into correct components with correct charges	6	2	4	3	15
Macroscopic explanations	2	5	2	3	12

Note. The number of responses in each column does not total 12 since responses could be included in multiple categories.

The current study also reported on levels of consistency between multiple representations of the same dissolution phenomenon demonstrated by participants. Johnstone's (1991) triangle illustrates the multiple levels of representing scientific phenomena: macroscopic, microscopic, and symbolic. Johnstone proposed that one of the difficulties in learning science involves a learner's inability to relate multiple representations of the same phenomenon to each other. Most learners focus on only one corner of the triangle, while teachers tend to teach from the middle of the triangle where all three levels interact. Numerous studies (Kozma, 2003; Kozma et al., 2000; Kozma & Russell, 1997; Wu et al., 2001; Wu & Shah, 2004) in comparisons of novices versus experts have found that

experts have the ability to move fluently between the three levels of representation to explain a chemical phenomenon. Table 5.2 includes a summary of the frequency for each level of consistency identified for participants' responses for the dissolution of the four ionic solids.

Table 5.2 Summary of Participants' Consistency Levels for the Dissolution of Four Ionic Solids

<i>Level of Consistency</i>	<i>Number of Participants</i>				
	KI	Pb(NO ₃) ₂	NaOH	Fe(NO ₃) ₃	Total
Complete consistency between all three responses	3	2	4	4	13
Partial consistency between all three responses	4	6	5	5	20
Complete consistency between two responses	1	1	2	2	6
Partial consistency between two responses	4	2	0	0	6
No consistency between any responses	0	1	1	0	2

Note. The maximum total available for each level of consistency would be 48.

Based on the academic background of the participants and their interest in science teaching, it can be assumed that they would fall somewhere in the middle on the continuum of novice and expert. Although there was fluctuation between the four ionic solids which dissolved, only two to four of the participants in the current study demonstrated complete consistency between the three representations for all four of the ionic solids. These pre-service science teachers could be described as being in the upper end of a novice-expert continuum. Only one participant in the current study demonstrated no consistency between the representations for all four ionic solids. This participant could be described as being in the lower end of a novice-expert continuum. The majority of the participants fell somewhere

in the middle of the continuum and exhibit several inconsistencies in their ability to represent dissolution phenomena correctly at multiple levels.

Despite the additional formal training in science and an expressed interest in teaching science to high school students, participants in the current study exhibited many of the same misconceptions about dissolution as previously reported. The participants also demonstrate difficulty in relating multiple levels of representation for the same chemical phenomenon as previously reported. Clearly, completing additional science coursework and an interest in science are not sufficient to challenge common misconceptions and promote deep conceptual understanding of the topic of dissolution.

Precipitation

Participants were also shown videos in which the solutions created in the first portion of the study were reacted to form two precipitates, lead (II) iodide and iron (III) hydroxide. After watching the videos, the participants were asked write a chemical equation and provide a drawing describing the reaction. Participants explained their responses and reasoning in an interview. An analysis of the participant's equations, drawings, and interview transcripts resulted in the identification of three categories of responses. Table 5.3 includes a summary of the frequency of each category identified in participants' responses for the precipitation of the two ionic solids.

Table 5.3 Summary of Participants' Responses by Thematic Category for the Precipitation of Two Ionic Solids

<i>Thematic Category</i>	<i>Number of Responses</i>		
	PbI ₂	Fe(OH) ₃	Total
Double displacement	11	17	28
Water as reactant	6	1	7
Solid as only product	6	5	11
Macroscopic explanation	4	4	8

Note. The number of responses in each column does not total 12 since responses could be included in multiple categories.

The most prevalent category of responses was double displacement. In this category, most participants explained their answers by using the term double displacement and saying that bonds break in the chemicals and then new bonds are formed to create two new products. While this is partially accurate, most participants made no distinction between the two products, the precipitate and spectator ions. In fact, most participants wrote the spectator ions together as a compound. Only one participant consistently identified the spectator ions, although not by that term, and explained that they would remain in solution. The current findings are similar to those previously reported on students' understanding of precipitation reactions and a lack of understanding of the role of spectator ions. (Chandrasegaran & Treagust, 2009; Chandrasegaran, Treagust, & Mocerino, 2007; Hinton & Nakhleh, 2000). As discussed by Kelly & Jones (2008), participants in the current study also had difficulty relating the dissolution of the ionic solids in the first part of the study to the formation of a precipitate when reacting two of the ionic solutions.

The researcher also determined levels of consistency between the two levels of representation, symbolic and microscopic, used with the precipitation reactions. Table 5.4

includes a summary of the frequency for each level of consistency identified for participants' responses for the precipitation of the two ionic solids. A considerably larger number of participants displayed complete consistency in their multiple representations of precipitation reactions than was seen with dissolution. There are several possible reasons for the differences in participants' consistency for dissolution and precipitation reactions. First of all, the researcher compared consistency for three items in the dissolution tasks and only two items in the precipitation task. There is a greater likelihood that participants would be able to demonstrate consistency between fewer responses, only two in the precipitation reactions versus three in dissolution.

Table 5.4 Summary of Participants' Consistency Levels for the Precipitation of Two Ionic Solids

<i>Level of Consistency</i>	<i>Number of Participants</i>		
	PbI ₂	Fe(OH) ₃	Total
Complete consistency between both responses	8	10	18
Partial consistency between both responses	4	2	6
No consistency between both responses	0	1	1

Note. The maximum total available for each level of consistency would be 24.

Another possible reason for increased consistency with precipitation reactions may be based upon the way this topic is taught in secondary schools. Precipitation reactions are typically referred to as double-displacement or double-replacement reactions in high school level chemistry texts (Davis, Metcfe, Williams, & Castka, 1999; LeMay Jr., Beall, Robblee,

& Brower, 2000). In fact, the textbook *Modern Chemistry* defines double-replacement reaction as “a reaction in which the ions of two compounds exchange places in an aqueous solution to form two new compounds” (Davis et al., 1999, p. 910). Additionally, these high school texts appear to focus on students recognizing the general form of the reaction, which is typically represented as $AX + BY \rightarrow AY + BX$. Participants in the current study appear to be proficient at writing equations for precipitation reactions in this format, with little thought given to the chemistry behind the reaction and how the two products differ. The researcher reviewed chemistry curriculum documents for five states in the southeastern United States and found the terms double displacement or double replacement as a specific type of reaction to be taught in high school chemistry courses (Georgia Department of Education, 2006; North Carolina Department of Public Instruction, 2004; South Carolina Department of Education, 2005; Tennessee Department of Education, 2008; Virginia Department of Education, 2003). Additionally, the researcher looked at two college chemistry texts and found that the terms double-displacement and double-replacement are not used (Brown, LeMay Jr., Bursten, & Burdge, 2003; Zumdahl & Zumdahl, 2000). These texts referred to this phenomenon as precipitation reactions. Specifically, Brown et al. define precipitation reaction as “a reaction that occurs between substances in solution in which one of the products is insoluble” (Brown et al., 2003, p G-9) The researcher suspects that this difference in terminology between high school and college chemistry may be partially responsible for common misconceptions regarding precipitation reactions reported both in previous studies and the current study.

Mental Models

This study attempted to characterize the mental models held by a group of 12 pre-service science teachers about the topics of dissolution and precipitation reactions through the analysis of participants' equations, drawings, and interviews. As stated by Greca & Moreira (2000), mental models are individualized internal representations. While each participant in the current study exhibited individual differences in their conceptualizations of the topics at hand, there were numerous instances in which participants exhibited similar ideas. It was expected that there would be some similarities in the mental models of these individuals, since they have all been provided instruction based upon the accepted conceptual model of these topics in chemistry courses. Greca and Moreira (2000) described conceptual models as consensus models created by researchers, teachers, engineers, etc. that aid in the comprehension or teaching of a system. Only two of the participants, one with a chemistry concentration and one in physics, exhibited mental models that were fairly consistent with the accepted conceptual models of dissolution and precipitation.

Results from this study align with Norman's (1983) instructional approach to mental models. Two aspects of Norman's approach seem to be directly applicable to the current study:

1. Mental models are incomplete...
3. Mental models are unstable: People forget the details of the system they are using, especially when those details (or the whole system) have not been used for some period. (p. 8)

Almost all of the participants in this study demonstrated incomplete mental models regarding the processes of dissolution and formation of precipitates. The researcher proposes that the

difficulty in using the appropriate particulate terminology by the participants may be related to Norman's idea that mental models are unstable and people forget the details of the system. Numerous participants used the terms atoms, ions, and molecules interchangeably while explaining their reasoning. However, when asked specifically about the differences in these terms, most of the participants could provide correct definitions of these terms. This assertion is supported by statements made by several of the participants when explaining their reasoning. For instance, Ben (P5) said several times during his interview "...a little bit of my chemistry is coming back to me..." and William (P12) said "Then I realized afterwards that I forgot my solubility rules" as he explained his responses for the dissolution of lead (II) nitrate.

The idea of contextualization is also important when considering the results of this study. Several researchers have theorized that learners may appear to hold multiple representations of the same concept depending upon the context (Duit, 1999; Pozo et al., 1999; Saljo, 1999; Schnotz & Preuss, 1999; Vosniadou, 1999). Based on these theories, it can be argued that experts may hold the same naïve or alternative conceptions as novices. The only difference being that experts are better at identifying the appropriate mental model to use based upon the situation. If this argument is true, then one must question when do pre-service teachers develop the ability to identify which appropriate mental model should be used in various situations?

Numerous participants in the study demonstrated inconsistencies in their equations, drawings and explanations between the four dissolution videos and then again between the two precipitation videos. This was especially surprising, since several of the participants

demonstrated mental models that aligned with the accepted conceptual model for some of the videos, but then exhibited mental models that were different for the remaining videos. It appears that participants with these inconsistencies may view each video as a separate contextual situation, rather than organizing them into the two contexts of dissolution and precipitation reactions. As novice learners, these participants appear to have yet developed the expert ability of selecting the appropriate mental model based upon similar contexts.

Implications

The results from this study have numerous implications including the teaching and learning of chemistry at high school and college. It also has implications in the area of teacher education, specifically in the preparation of science teachers. As such, the researcher envisions the results of this study potentially influencing both the development of content knowledge and pedagogical content knowledge of pre-service science teachers.

First and foremost, this study supports previously reported findings of common misconceptions about dissolution and precipitation reactions and the inability of high school and college learners to use multiple representations to explain a chemical phenomenon. Despite the additional science background and intrinsic motivation of the current participants, many still incorporated misconceptions into their mental models of dissolution and precipitation.

The researcher strongly suggests that serious consideration be given to replacing the terms double-displacement or double-replacement with precipitation reactions in high school textbooks and state level curriculum documents. Although, the use of these terms is probably an attempt to simplify the chemistry content, these terms and how they are defined may be

partially responsible for creating misconceptions. The researcher also strongly suggests that state curriculum documents be modified to emphasize the role of multiple representations in understanding chemistry. The *National Science Education Standards* (National Research Council, 1996) state the following:

High-school students develop the ability to relate the macroscopic properties of substances that they study in grades K-8 to the microscopic structure of substances. This development in understanding requires students to move among three domains of thought—the macroscopic world of observable phenomena, the microscopic world of molecules, atoms, and subatomic particles, and the symbolic and mathematical world of chemical formulas, equations, and symbols. (p. 177)

While numerous states have updated the science curriculum to align with the *National Science Education Standards*, the state curriculum documents reviewed by this researcher do not explicitly state the expectation that students be able to move among the three levels of representation as described in the national standards. As a former high school chemistry teacher, the researcher understands the pressures created by the current atmosphere of accountability in public education. In response to that pressure many public school teachers teach only that which is explicitly stated in the state curriculum documents because that is what is tested. If the state curriculum documents continue to specifically refer to precipitation reactions as double-displacement or double-replacement reactions, then teachers will feel the need to use those exact terms with their students despite the potential misunderstandings created by their use. On the opposite side of the coin is the omission of essential skills in state level curriculum documents. The failure to specifically reference the requirement of high school science students to be able to move among the three domains: macroscopic, microscopic, and symbolic, may possibly result in teachers focusing on

problem-solving and quantitative skills in order to prepare students to pass a test. Although teachers may feel this is an important skill, if it is not tested, then it will most likely not be taught. This is supported by Gabel's (1993) research where she stated that chemistry teachers "emphasize the symbolic level and problem-solving level at the expense of the phenomena and particle levels." (p. 193)

Data from this study appear to support the idea that many pre-service science teachers need to develop a deeper understanding of their content knowledge. The researcher provides the following suggestions in regards to improving content knowledge.

Science instructors at both the high school and college levels should continually reflect upon their methods of instruction and seek ways to improve student learning. Numerous studies have reported on the effects of a variety of instructional strategies, such as, emphasizing the particulate nature of matter, the use of particulate level animations and simulations, and student generated particulate level drawings or explanations, on improving students' understanding of multiple levels of representations and specific chemistry topics, including dissolution and precipitation reactions (Ardac & Akaygun, 2004; Mauammer Calik, Ayas, Coll, Unal, & Costu, 2006; Chandrasegaran & Treagust, 2009; Kelly & Jones, 2007, 2008; Tien et al., 2007). Chemistry instructors should be encouraged to incorporate strategies shown to be effective at promoting conceptual understanding of chemistry and to implement their own creative instructional strategies grounded in this body of research. Additionally, science educators and chemical educators need to pursue additional research into effective teaching strategies for improving students' conceptual understanding of the topics of dissolution and precipitation reactions.

As a practicing science educator involved in the preparation of future science teachers, the researcher is well aware of the constraints of college campuses in terms of a science course serving students in multiple majors. As such, very few college science faculty members are willing to modify their course and instructional methods to tailor instruction to meet the needs of one specific program, such as a science teacher preparation program. While the researcher would argue, that the previously stated implications if implemented would result in improved learning for all students enrolled in chemistry regardless of their majors, she also suggests that science educators involved in teacher preparation must also share in the responsibility of addressing this situation.

The researcher suggests that science education faculty members involved in teaching instructional methods courses consider incorporating the ideas of modeling, specifically mental and conceptual models, and the use of multiple representations into those teacher preparation courses. For instance, research on laboratory activities based upon the Model-Observe-Reflect-Explain (MORE) framework has shown to be effective at promoting conceptual change (Mattox, Reisner, & Rickey, 2006; Tien et al., 2007). Teacher educators could easily implement these laboratory activities or others based upon the MORE framework in their instructional methods courses. This type of activity could serve two purposes. First, it would model an effective instructional strategy grounded in the research for future science teachers to learn how to use in their own classrooms. Secondly, it would provide an opportunity for pre-service science teachers to think about and express their mental models on a particular science topic. Through class discussions related to modeling, future science teachers may recognize inconsistencies in their own mental models. This type

of social interaction may help to promote conceptual change in pre-service science teachers and teach these future educators strategies for promoting conceptual change with their future students.

Science educators involved in teacher preparation can also implement how to teach with multiple representations in their instructional methods courses. Gabel (1993) stated “even though it (chemistry) is taught at three levels, insufficient connections are made between the three levels...” (p. 193). This is probably especially true at the college level where instructional time is limited. Although some college science faculty may not agree with the value of explicitly explaining the connections between the three levels in their courses, science educators tasked with preparing future science teachers should certainly agree that this topic falls within the purvey of developing pedagogical content knowledge in pre-service science teachers. Implementation of these types of activities in instructional methods courses could serve to improve both the content knowledge and pedagogical content knowledge of pre-service science teachers.

Future Research

Given the small sample size of the current study, the researcher does not attempt to generalize the findings to a larger population of pre-service science teachers. Therefore, future research could replicate this study with other pre-service science teachers at this university and other universities to determine if the results are comparable to those reported here. Additionally, 10 of the 12 participants in the current study were completing a concentration in biology. The two participants who were completing other concentrations, one in chemistry and one in physics, exhibited mental models that were closest to the

accepted conceptual models of dissolution and precipitation. Future research could compare the results of pre-service science teachers completing different science concentrations to see if differences exist in their mental models of dissolution and precipitation reactions based upon the area of concentration.

Since the pre-service science teachers in the current study displayed mental models that were not entirely consistent with accepted conceptual models, one must question at what point do prospective science teachers' mental models align with the accepted conceptual models that would hopefully be used in teaching future science students? Do these prospective science teachers' mental models change during student teaching, prior to graduation, or do they enter the teaching profession with incomplete and unstable mental models? If new teachers enter the classroom with incomplete and inaccurate mental models, what "conceptual" models do these teachers convey to their students? Do they trust their own mental models or do they resort to conveying the conceptual models provided in textbooks, state curriculum documents, and/or other teaching materials? All of these questions suggest direction for future research in an effort to improve science learning for all.

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APPENDICES

APPENDIX A

Pilot Study Questionnaire

1. When solid lead (II) nitrate ($\text{Pb}(\text{NO}_3)_2$) is placed in a beaker of water,
 - a. it melts into the liquid phase.
 - b. it separates into individual molecules.
 - c. it separates into its component ions.
 - d. it breaks apart into individual atoms.
2. Write the chemical equation that represents the chemical phenomenon described in item #1.
3. In the space below, draw your image of how the phenomenon in item #1 would look if you viewed it under an extremely powerful scope that allowed you to see each component separately. Explain your drawing and why this phenomenon occurs.

Drawing

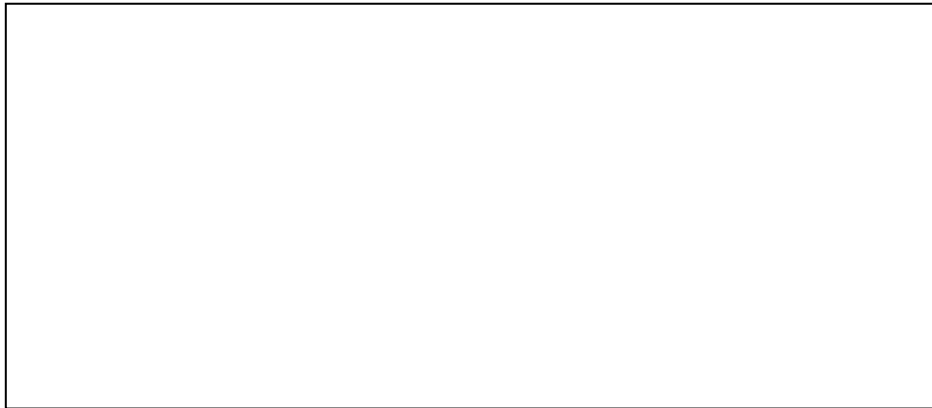


Explanation:

4. When solid potassium iodide (KI) is placed in a beaker of water,
 - a. it melts into the liquid phase.
 - b. it separates into individual molecules.
 - c. it separates into its component ions.
 - d. it breaks apart into individual atoms.
5. Write the chemical equation that represents the chemical phenomenon described in item #4.

6. In the space below, draw your image of how the phenomenon in item #4 would look if you viewed it under an extremely powerful scope that allowed you to see each component separately. Explain your drawing and why this phenomenon occurs.

Drawing



Explanation:

7. When aqueous lead (II) nitrate ($\text{Pb}(\text{NO}_3)_2$) is combined with aqueous potassium iodide (KI) in a beaker, solid lead (II) iodide (PbI_2) is formed. Write a chemical equation that represents this chemical phenomenon.
8. In the space below, draw your image of how the phenomenon in item #7 would look if you viewed it under an extremely powerful scope that allowed you to see each component separately. Explain your drawing and why this phenomenon occurs.

Drawing



Explanation:

APPENDIX B

Study Questionnaire

3. 1. When solid ~~lead (II) nitrate ($\text{Pb}(\text{NO}_3)_2$)~~potassium iodide, KI, is placed in a beaker of water,
- e. it melts into the liquid phase.
 - f. it separates into individual molecules.
 - g. it separates into its component ions.
 - h. it breaks apart into individual atoms.
4. 2. Write the chemical equation that represents the chemical phenomenon described in item #1.
3. In the space below, draw your image of how the phenomenon in item #1 would look if you viewed it under an extremely powerful scope that allowed you to see each component separately. Explain your drawing and why this phenomenon occurs.

Drawing



Explanation:

|

a.4. When solid lead (II) nitrate, $\text{Pb}(\text{NO}_3)_2$, ~~potassium iodide (KI)~~ is placed in a beaker of water,

- a.e. it melts into the liquid phase.
- a.f. it separates into individual molecules.
- a.g. it separates into its component ions.
- a.h. it breaks apart into individual atoms.

b.5. Write the chemical equation that represents the chemical phenomenon described in item #4.

e.6. In the space below, draw your image of how the phenomenon in item #4 would look if you viewed it under an extremely powerful scope that allowed you to see each component separately. Explain your drawing and why this phenomenon occurs.

Drawing



Explanation:

7. When aqueous potassium iodide, KI, ~~lead (II) nitrate ($\text{Pb}(\text{NO}_3)_2$)~~ is combined with aqueous lead (II) nitrate, $\text{Pb}(\text{NO}_3)_2$, ~~potassium iodide (KI)~~ in a beaker, solid ~~lead (II) iodide (PbI_2)~~ lead (II) iodide, PbI_2 , is formed. Write a chemical equation ~~that~~ that represents this chemical phenomenon.

8. In the space below, draw your image of how the phenomenon in item #7 would look if you viewed it under an extremely powerful scope that allowed you to see each component separately. Explain your drawing and why this phenomenon occurs.

Drawing



Explanation:

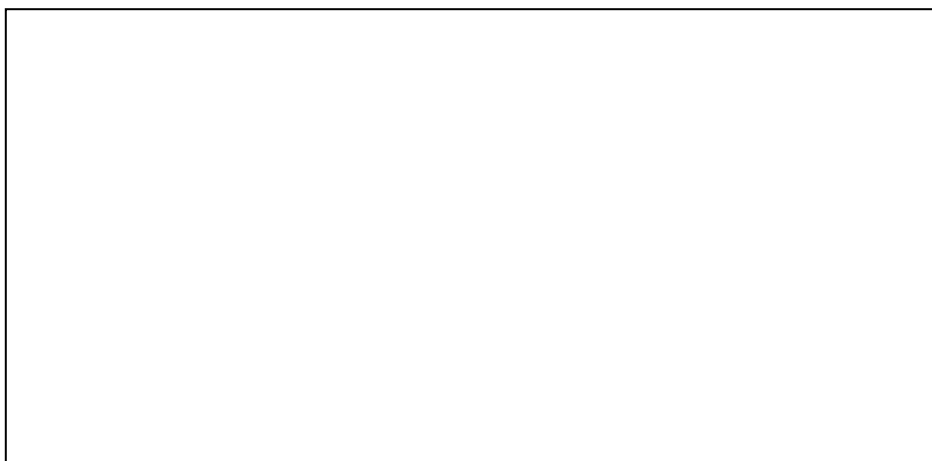
| a.9. When solid ~~lead (II) nitrate ($\text{Pb}(\text{NO}_3)_2$)~~ sodium hydroxide, NaOH, is placed in a beaker of water,

- a. it melts into the liquid phase.
- b. it separates into individual molecules.
- c. it separates into its component ions.
- d. it breaks apart into individual atoms.

| b. 10. Write the chemical equation that represents the chemical phenomenon described in item #9.

11. In the space below, draw your image of how the phenomenon in item #9 would look if you viewed it under an extremely powerful scope that allowed you to see each component separately. Explain your drawing and why this phenomenon occurs.

Drawing



Explanation:

12. When solid ~~lead (II) nitrate ($\text{Pb}(\text{NO}_3)_2$)~~ iron (III) nitrate, $\text{Fe}(\text{NO}_3)_3$, is placed in a beaker of water,

- it melts into the liquid phase.
- it separates into individual molecules.
- it separates into its component ions.
- it breaks apart into individual atoms.

13. Write the chemical equation that represents the chemical phenomenon described in item #12.

14. In the space below, draw your image of how the phenomenon in item #12 would look if you viewed it under an extremely powerful scope that allowed you to see each component separately. Explain your drawing and why this phenomenon occurs.

Drawing



Explanation:

15. When aqueous sodium hydroxide, NaOH, ~~lead (II) nitrate ($\text{Pb}(\text{NO}_3)_2$)~~ is combined with aqueous iron (III) nitrate, $\text{Fe}(\text{NO}_3)_3$, ~~potassium iodide (KI)~~ in a beaker, solid ~~lead (II) iodide (PbI_2)~~ iron (III) hydroxide, $\text{Fe}(\text{OH})_3$, is formed. Write a chemical equation ~~that~~ that represents this chemical phenomenon.

16. In the space below, draw your image of how the phenomenon in item #16 would look if you viewed it under an extremely powerful scope that allowed you to see each component separately. Explain your drawing and why this phenomenon occurs.

Drawing



Explanation:

APPENDIX C

Interview Guide

(Below is a list of possible questions to be used during the interview process. Since the interview is being used as follow-up and a way of clarifying participant's responses on the written questionnaire, all questions may not be asked and additional questions may be used based upon participant's responses.)

- 1) Explain why you selected (insert answer) in item #1/#4/#9/#12.

- 2) Explain how you determined the chemical equation for video #1/#2/#3/#4/#5/#6.

- 3) Explain your drawing of the chemical phenomenon in video #1/#2/#3/#4/#5/#6.

- 4) If the participant selects different answers for items 1,4,9,12 then ask the following questions:
 - a. What do you think is the difference between solid #1 and solid #2/#3/#4?

 - b. Explain why you think solid #1 and #2/#3/#4 would react differently when placed in water.

- 5) Why do you think some solids dissolve in water and others do not?

- 6) You may have noticed that some solids dissolve faster when stirred. Do you have any ideas about why this happens?

- 7) You may have noticed that some solids dissolve faster when placed in warm or hot water. Do you have any ideas about why this happens?