Experienced High School Chemistry Teachers’ Conceptions of Chemical Equilibrium

in Terms of Rates of Reaction

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Much research has been conducted regarding student alternative conceptions in chemistry, and a significant amount of work has focused on the areas of chemical equilibrium and reaction rates. Less research has focused on teachers’ alternative conceptions in these areas, and most of this work has studied the conceptions of pre-service and novice chemistry teachers. Teachers’ understanding of chemistry concepts, as well as the way they integrate these topics, play a crucial role in their ability to teach for understanding and promote conceptual change in their students. This study investigated experienced high school chemistry teachers’ conceptions about chemical equilibrium as it relates to reaction rates. Thirteen teachers of advanced (AP and IB) chemistry, with an average of 11.4 years of experience, completed the Chemical Equilibrium Concepts Test (CECT, Hackling and Garnett, 1985), and participated in interviews containing graphing tasks. Information about each teacher’s alternative conceptions regarding equilibrium and reaction rates was ascertained, as well as information about how these topics were integrated in their minds and in their classrooms. The teachers in the study maintained many of the same alternative conceptions held by students and pre-service/novice teachers. The concepts of reaction rates as they relate to chemical equilibrium were not well understood. The teachers had difficulty describing changes to an equilibrium system in terms other than the algorithmic statements of Le Châtelier’s principle and were generally unable to draw accurate concentration and rate graphs for these changes. Those teachers who held primary certifications in chemistry were better able to describe equilibrium in terms of reaction rates, scored higher on the CECT, and maintained fewer alternative conceptions. The results of this study have important implications for chemistry education. A greater focus on the integration of chemistry topics is needed in textbooks and in course curricula. Teacher training and professional development should include courses that focus on mastering the nuances and interconnectedness of topics in chemistry, as well as a study of the research that has been conducted with respect to the alternative conceptions of both teachers and students.
Dedication

For Jayson.

May you always follow your heart and mind to achieve love, knowledge, success, and happiness.
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Chapter 1

Introduction

1. Overview

A great deal of time is spent by educators trying to determine what students know, and subsequently, how to teach them appropriately. There has been quite a bit of research conducted regarding student alternative conceptions in chemistry, with a good deal of work focused specifically on the area of chemical equilibrium. Less research has focused on teachers’ alternative conceptions in this area. Teachers’ understanding of chemistry concepts, as well as the integration of topics within the curriculum, plays a crucial role in their ability to teach for conceptual understanding and conceptual change in their students. It is hoped that this research may be used to inform teacher preparation programs, inspire professional development workshops, and be a source of rich discussion concerning this area of chemistry teaching.

1.1. Purpose of the Study

The goal of this study was to explore experienced teachers’ alternative conceptions in the area of chemical equilibrium, and their ability to explain the concepts of chemical equilibrium in terms of reaction rates. Interviews, along with an online assessment, were used to probe teachers’ understanding of the concepts within the construct of chemical equilibrium. The interviews consisted of (a) explanations of general concepts within the construct of equilibrium, (b) predictions of the outcomes of events such as changing equilibrium conditions, (c) explanations about the events in terms of concentrations and reaction rates, (d) graphing tasks, and (e) discussions of the integration of equilibrium and reaction rates in the classroom.

1.2. Research Questions

This study is based on a call from researchers that further work is needed to show how teachers’ subject matter knowledge and alternative conceptions affect teaching and learning (Cheung, 2009a, 2009b; Kruse & Roehrig, 2005; Talanquer, Scantlebury, & Dukerich, 2009). The study presupposes that the ability of teachers to identify and address student alternative conceptions is based on their own content knowledge (Piquette & Heikkinen, 2005), that teachers have been found to maintain the same alternative conceptions as students with respect to chemical equilibrium and reaction rates (Banerjee, 1991), and that teachers choose how to teach topics based upon their own conceptions and subject matter structure (Lederman, Gess-Newsome, & Latz, 1994). This research aims to (a) identify the alternative conceptions held by experienced chemistry teachers regarding chemical equilibrium and reaction rates, (b) identify how these teachers use the concepts of reaction rates to describe chemical equilibrium on a submicroscopic level, and (c) explore how these teachers are integrating chemical equilibrium and reaction rates within their classrooms.
Three research questions guided the development of this study:

1. What, if any, alternative conceptions do experienced chemistry teachers hold about chemical equilibrium and reaction rates? Specifically:
   a. What alternative conceptions about chemical equilibrium do teachers of chemistry hold, and how common are these alternative conceptions?
   b. What alternative conceptions about rates of reaction do teachers of chemistry hold, and how common are these alternative conceptions?
   c. Is there any relationship between the alternative conceptions about chemical equilibrium and reaction rates and the certification and teaching backgrounds of these teachers?

2. How do teachers of chemistry use the concepts of reaction rates to describe different aspects of chemical equilibrium on a submicroscopic level? Specifically, how do teachers of chemistry:
   a. describe the approach to equilibrium in terms of the rates of the forward and reverse reactions?
   b. describe the characteristics of equilibrium in terms of the rates of the forward and reverse reactions?
   c. describe changes to the equilibrium condition and the return to equilibrium (Le Châtelier’s principle) in terms of the rates of the forward and reverse reactions?
   d. describe the addition of a catalyst to a reaction at equilibrium in terms of rates of the forward and reverse reactions?
   e. How do teachers describe these concepts on a submicroscopic level?
   f. Is there a relationship between teachers’ educational and teaching background and their ability to describe equilibrium concepts in terms of rates of forward and reverse reactions?

3. How do teachers present chemical equilibrium and reaction rates in their classrooms? Are they integrated? Why or why not? Specifically,
   a. Do teachers describe equilibrium in terms of reaction rates for forward and reverse reactions in their classroom? Why or why not?
   b. Is there a relationship between teachers’ educational/teaching background and their practice of describing equilibrium in terms of reaction rates?
   c. Is there a relationship between teachers’ knowledge about chemical equilibrium and the practice of describing equilibrium in terms of reaction rates in their classroom?

A more in-depth discussion regarding students’ and teachers’ alternative conceptions in chemistry, chemical equilibrium, and reaction rates, as well as a discussion of the pedagogical content knowledge of teachers occurs in the next section, which reviews the literature with respect to these ideas.
1.3. Significance of the Study

There has been quite a bit of research conducted in the area of student alternative conceptions in chemistry, with a good deal of work focused specifically on the area of chemical equilibrium. Much less research has focused on teachers’ alternative conceptions in this area, and much of that work has been quantitative in nature, describing the results of pencil and paper test results. After completing a study on the conceptions of chemistry teachers, Kruse and Roehrig (2005) concluded that further studies would be needed to show how subject matter knowledge affects teaching and learning, as well as teachers’ abilities to gather information about their students’ knowledge. Derek Cheung also suggested that alternative conceptions held by chemistry teachers needed to be studied since, just like true understanding, alternative conceptions can be passed to students from teachers (2009b). The results of this study will add to the body of knowledge that exists for improving the development of teacher education programs and the pedagogical content knowledge of chemistry teachers. Results may be used to inform teachers and professional development programs, and could be the source of rich discussion, publications, and in-service workshops concerning this area of chemistry teaching.

1.4. Limitations of the Study

Though the interview data gained from this study provides a rich description of the equilibrium conceptions of the teacher participants, the study is ultimately limited by the small sample size of participants. In addition, since the teacher participants all teach in Long Island, New York schools, the results may not be generalizable to any group of educators teaching outside of the region, where certification requirements and teaching responsibilities differ. The sample of participants in the study therefore represents a convenience sample. Interview data was collected regarding teacher practice. Since that information was self-reported by the teacher participants, and was not checked by field studies, that data includes a certain amount of uncertainty due to bias and misrepresentation. Not to be ignored is the bias of the researcher, who may interpret interview responses differently than a participant intended. Finally, the nature of those who volunteer to participate in a research study such as this must be considered. One would expect that only those who are relatively confident in their knowledge and teaching strategies, as well as those who are interested in professional development, would be interested in participation.

1.5. Organization of Dissertation

This dissertation is divided into the following chapters: Chapter 1 (the current chapter) has outlined the purpose for and significance of the study, as well as defining the research questions that guided the development, collection and analysis of the study data. Chapter 2 reviews the relevant research pertaining to the study. First, this chapter includes literature focused on constructivism, alternative conceptions, students’ and teachers’ alternative conceptions in chemistry, sources of alternative conceptions, and how alternative conceptions can be measured, addressed, and changed. Next, the review turns to a discussion of chemical equilibrium, reaction rates, and Le Châtelier’s principle, outlining important research on student and teacher alternative conceptions within these topics, the importance of the integration of these topics, and the use of graphing as an important tool for teaching and assessing these topics. Finally, the
literature with regard to teachers’ subject matter knowledge and structure is explored, including how subject matter knowledge is related to pedagogical content knowledge, and how these topics were considered in the theoretical and conceptual frameworks for the study.

Chapter 3 outlines the research methods for the current study. Beginning with the methodological framework, this chapter includes a description of prior work leading up to the current study, including two pilot studies. Next, information concerning study materials (IRB approval, interview guidelines, assessment and participants) is provided, along with the procedure used with all teacher participants. Last, information concerning the analysis of results is provided, including coding information for the qualitative data obtained from the interviews.

Results and major findings of the study are presented in Chapter 4. First, information collected about the teacher participants is described and tabulated. The bulk of this chapter then focuses on the conceptions and alternative conceptions that these teachers maintained about equilibrium and reaction rates, especially those that hindered their ability to describe equilibrium in terms of rates of reactions. A major portion of these results describes the results of the graphing task that was used to probe the richness of each teacher’s understanding of what happens to a system (from the standpoint of changes to concentration of species and changes to rates of the forward and reverse reactions) once it is disturbed from an equilibrium state by adding additional reactants, increasing the temperature, or decreasing the volume. Teachers’ conceptions regarding the addition of a catalyst to the system as well as the addition of water was also probed, and is presented. Next, teachers’ educational and teaching backgrounds, certifications held, and years of experience was compared to the number of alternative conceptions maintained by the teachers, and their scores on the Chemical Equilibrium Concepts Test (CECT). This is followed by a description of the language that these teachers used to describe concepts in equilibrium. Also included in this chapter is a discussion of an emergent finding regarding the ability of the graphing tasks to affect conceptual change. Finally, data obtained concerning these teachers’ integration of the two topics is presented in this chapter.

Chapter 5 discusses the findings of the study, and its implications for teaching and learning. This includes implications for textbook and curricula development, and certification and teacher preparation program requirements. Suggestions for professional development opportunities, based on the study are presented, as are recommendations for classroom practice. Finally, the assumptions and limitations of the study are discussed, and the research questions are revisited.
2. Introduction

This review of the literature is structured to logically develop the ideas that provide the rationale for the current research study. After an overview of what makes chemistry difficult to learn and teach, the review will be divided into three major sections. First, it will focus on the research regarding alternative conceptions, and how they arise from constructivism. This section will include the alternative conceptions of chemistry students and teachers, the sources of these alternative conceptions, and how they are measured and addressed in the classroom. Next, the review will explore research specifically regarding chemical equilibrium, rates of reaction, and Le Châtelier’s principle. This will include the difficulty with respect to teaching these topics, their placement within the general chemistry curriculum, and the different ways their concepts can be explained. This section will review the relevant literature regarding students’ and teachers’ alternative conceptions specific to the topics of equilibrium and rates of reaction, as well as the integration of these two themes in the chemistry curriculum. Last, the review will examine the frameworks for this study, including chemistry teachers’ subject matter knowledge, subject matter structure, and pedagogical content knowledge.

2.1. The Difficulty of Chemistry and its Teaching

David Treagust (2007) summarized the content within a chemistry curriculum as problematic. The nature of chemical concepts is abstract and hard to visualize, the language is complex, and concepts are disseminated and compacted into sometimes overwhelming courses that simply add information as it is discovered (Bodner, 1991; Gilbert, 2004). Ideas in chemistry must often be understood on three levels: the macroscopic, submicroscopic, and symbolic (Johnstone, 1991). The materials are often unfamiliar to the students, and the structure of the curriculum is often undefined and varied from textbook to textbook and from course to course (Gabel, 1999). Chemistry is very reliant on the concepts of physics, and the models that the theoretical concepts depend on are not always logical to the learner (Taber, 2001). In addition, understanding topics within the chemistry curriculum is reliant on previous and ill-understood concepts, understandings, and models (Nakhleh, 1992). Together, these issues keep chemistry on the list of “killer courses” (Rowe, 1983). When concepts are not logical, they are bound to be misunderstood, leading to the conditions necessary for the formation of alternative conceptions.

2.2 Alternative Conceptions in Chemistry

Constructivism

Constructivism is a theory of knowledge that defines knowledge as constructed in the minds of learners. It was developed from Piaget’s theory of intellectual development, in which
knowledge is considered to be a life-long constructive process, and deals with the organization, structuring, and restructuring of experiences. Piaget, whose early work was in biology, related the development of knowledge to the development of an organism, through the process of equilibration (Fosnot & Perry, 1996). As more is experienced, existing schemes of thought are modified and/or expanded. In constructivism, knowledge is a search for fit, rather than a match with reality. As long as the knowledge functions satisfactorily, it will remain the prevailing knowledge. As written by Heisenberg, “…we have to remember that what we observe is not nature in itself but nature exposed to our method of questioning” (1958, p. 58). To this, Bodner suggested that “the problem with constructivism arises when one tries to look at the logical consequences of the assumption that knowledge is constructed in the mind of the learner” (Bodner, 1986, p. 4). In other words, constructivism sets the conditions that are necessary for the development of alternative conceptions, which are discussed in the next section.

**Alternative Conceptions**

If knowledge is constructed in the minds of learners, some of that knowledge will be “mental representations of concepts that do not correspond to currently held scientific theory” (Skelly & Hall, 1993, p. 3). Misconceptions that arise from the attempt to make sense of everyday experiences with phenomena are called *alternative (alternate) conceptions* or *naïve conceptions*. In chemistry, however, the term *misconception* is sometimes more appropriate because the misconceptions do not always occur as a result of an experiential interaction with matter; rather, they occur as a function of instruction. In all areas of knowledge, including chemistry, these alternative conceptions are plentiful, quite steadfast, highly resistant to instruction, and can hinder future learning. It takes careful planning to change students’ minds about what they think they understand. Alternative conceptions begin early (Osborne & Cosgrove, 1983), and students cannot properly build upon fundamentals that are not understood (Nakhleh, 1992). Books, research studies and comprehensive reviews of the research dealing with the alternative conceptions of chemistry students are plentiful (Chiu, 2007; Garnett, Garnett, & Hackling, 1995; Garnett & Hackling, 1984; Hackling & Garnett, 1985; Horton, 2007; Kind, 2004; Nakhleh, 1992; Özmen, 2004; Taber, 2002a, 2002b), as are research studies dealing with methods for the identification and assessment of these alternative conceptions (Bowen & Bunce, 1997; Chandrasegaran, Treagust, & Mocerino, 2007; Gorodetsky & Gussarsky, 1986; Mulford & Robinson, 2002; Özmen, 2008; Peterson, Treagust, & Garnett, 1989; Voska & Heikkinen, 2000). The next sections explore the chemical alternative conceptions of students and their sources, and how chemistry instruction might be adapted to combat them.

**Students’ Alternative Conceptions in Chemistry**

A comprehensive literature review compiled by Patrick Garnett, Pamela Garnett, and Mark Hackling showed that alternative conceptions permeate virtually every topic in chemistry, including the particulate nature of matter, covalent bonding, molecules and intermolecular forces, chemical equations, chemical equilibrium, acids and bases, oxidation and reduction, and electrochemistry (Garnett et al., 1995). A more recent comprehensive bibliography on the research dealing with scientific misconceptions was compiled by Duit (2009). Specific examples of studies regarding the chemical conceptions of students are discussed later in this review.

Even after studying chemistry in college, alternative conceptions often persist. Bodner reported on a conceptual chemistry exam that was given to incoming graduate students of chemistry at Purdue University (Bodner, 1991). He found that alternative conceptions in
chemistry are plentiful, even at the graduate level, across topics such as the particulate nature of matter, the relationship between temperature and heat, reactions and stoichiometry, colligative properties of solutions, gases and pressure, and density. He concluded that it was important to study the alternative conceptions that students form early in their careers because they are 

…so resistant to instruction that a significant fraction of the population retains them even after the 500 hours of laboratory work and 400 hours of lectures…mandated by the ACS Committee on Professional Training. (Bodner, 1991, p. 11).

He also noted that the responses on the conceptual exam showed that students had knowledge without true understanding of the concepts in chemistry.

_Teachers’ Alternative Conceptions in Chemistry_

Of interest are the comparatively small number of studies that aimed to determine the chemical knowledge and alternative conceptions held by pre-service and in-service chemistry teachers, since it can be hypothesized that, just like true understanding, alternative conceptions can be passed to students from teachers (Cheung, 2009b). Most of those studies have involved only general chemistry knowledge, pre-service teachers, and single-concepts within the chemistry curriculum (Azizoglu, Alkan, & Geban, 2006; Canpolat, Pinarbasi, & Sözbilir, 2006; Cheung, 2009b; Kolomuç & Tekin, 2011; Kruse & Roehrig, 2005; Pinarbasi, Sozbilir, & Canpolat, 2009; Quílez, 2004; Quílez-Pardo & Solaz-Portolés, 1995; Talanquer et al., 2009). Overall, these studies have concluded that teachers often tend to hold the same alternative conceptions as their students.

One of the most striking of these studies was that of Kruse and Roehrig (2005), who conducted a mixed-methods study to assess the various conceptions of chemistry teachers and to compare them with student conceptions. It also aimed to determine how the conceptions of chemistry teachers matched their demographic characteristics, namely, whether they had a degree in chemistry, and whether they were teaching in or outside of their certification area. Forty-five teachers from an urban school setting who were participating in a professional development activity relating to student misconceptions were given the _Chemical Concepts Inventory_ (CCI) developed by Mulford and Robinson (2002), which is discussed later in this review. The concepts inventory was scored and returned to the teachers for discussion after they had read Mulford and Robinson’s research report. The concepts inventory scores and demographic information were used to construct quantitative results, and interviews were conducted in order to collect qualitative data. Although the teachers scored higher on the CCI than the students with whom they were compared, the teachers displayed similar alternative conceptions to students regarding chemical formulas, equations, energetics of bonding, the submicroscopic nature of atoms, heat and temperature, solution chemistry, and macroscopic versus submicroscopic properties of substances. One meaningful finding of this study was a significant difference in the CCI scores of teachers who were teaching in and out of their discipline (87.2% and 72.2%, respectively). A crucial finding of the study was that the teachers did not realize their alternative conceptions about chemistry before taking the CCI because they did not often get the chance to challenge their own conceptions in chemistry. This was discovered during the discussion part of the study, where several teachers first asked for clarification of a topic (for example, properties of atoms versus bulk substances), and remarked
that that was not what they teach. Kruse and Roehrig suggested that because of this, alternative conceptions could be passed to students through instruction. During the interviews, it was found that teachers who were not comfortable with their chemistry knowledge tended to superficially teach – or not teach at all – concepts about which they felt less confident (Kruse & Roehrig, 2005).

In a telling study by Sheehan, Childs, and Hayes (2011), it was found that teachers’ alternative conceptions in chemistry do not diminish during their professional training. Beginning with the assumption that incoming students into a teacher-training program in chemistry possess alternative conceptions, they conducted a study to determine whether pre-service science teachers’ alternative conceptions changed over the course of the four-year program. The researchers used a 17-item instrument to test students’ conceptions in the areas of the particulate nature of matter, bonding, and chemical equilibrium. The students were tested during each year of the pre-service program. It was found that the scores on the assessment were very low (the average score was 30.8%), and many alternative conceptions were identified to be similar to those identified in previous studies. A major finding of the study was that the number of alternative conceptions was similar among all four years of study, and that the same alternative conceptions were identified at each level, meaning that alternative conceptions were not being corrected over the course of the program. A second major finding was that students’ area of specialization affected the number of alternative conceptions, with lower number of alternative conceptions for those specializing in the physical sciences (as opposed to biological science). It was also found that female pre-service teachers held a greater number of alternative conceptions than their male counterparts (Sheehan et al., 2011).

**Sources of Alternative Conceptions of Teachers and Students**

The reasons for the development of these alternative conceptions are as plentiful and as diverse as the topics that are misunderstood (Gable, 1999; Garnett et al., 1995; Nakhleh, 1992; Skelly & Hall, 1993). First, the use of everyday language in the classroom is problematic. Garnett, et al. (1995) suggested the word “particle” for consideration. In everyday language, a particle is something small but can be seen, such as a speck of dust. In chemistry, however, “particles” are individual atoms, ions, or molecules, too small to be observed. Johnstone and Selepeng (2001) found that not only are everyday words with different meanings in chemistry (such as “mass”) problematic, but common language was also misunderstood, especially for English language learners. These words were often confused for sound-alike or look-alike words (e.g., “contrast” vs. “contract”; “isolate” vs. “operate”), confused with words with opposite meanings (e.g., “abundant” confused for “shortage”), or had imprecise meanings (e.g., “limit” and “percentage” described as “average”). Gabel (1999) pointed out that common phrases such as, “the candy melts in your mouth” is probably intended to mean that the candy has dissolved in the mouth, but students only store the common definitions in their long-term memory. A test given to students by Nakhleh (1992) revealed how the phrase, “molecules expand on heating” was incorrectly interpreted as the molecules simply getting bigger rather than filling the container. Bodner (1991) suggested that teachers are sometimes guilty of improper use of language in the classroom. Also to be considered, are the symbols used in chemistry. Some elements, for example, have symbols from their Latin names; others do not (Skelly & Hall, 1993).

The use of anthropomorphism by students when describing atoms is a frequent type of alternative conception. Students think that atoms are alive, and this confusion might stem from
the fact that students learn about living cells as the fundamental building blocks of organisms before they learn about atoms as the fundamental building blocks of matter (Garnett et al., 1995). Since our current view of constructivist learning suggests that a learner will organize new information by relating it to knowledge they already possess, it would be interesting to test Garnett’s idea by observing if the same anthropomorphism exists with students who learn chemistry before biology (atoms before cells). In a study conducted by Coll and Treagust (2001), it was found that students used anthropomorphic statements to explain concepts in chemical bonding. Statements such as, “…lithium…will want to give an electron to chlorine,” and, “[tin] plays more friendly with his mates,” were common ways that students of all ages (high school, college, and graduate school) described bonding phenomena. Though this study only looked at six learners, the results are generalizable to a larger group, as shown by other research studies.

Many alternative conceptions are related to the problems that students have visualizing matter in terms of particles. Alternative conceptions that substances are homogeneous and not made up of discrete particles are common and students tend to assign macroscopic properties to submicroscopic particles (Garnett et al., 1995). For example, a student might suggest that individual molecules of water expand when heated, or that individual atoms of sulfur are solid, brittle, yellow, and have a melting point of 113°C (Kruse & Roehrig, 2005). Johnstone added that students, unlike chemists, have a difficult time switching between the three modes of chemical thought: the macroscopic, the submicroscopic, and the symbolic (Johnstone, 1991), and there is a lack of attention to the submicroscopic level in the classroom (Garnett et al., 1995). This is further compounded by the fact that students also tend to reduce their understanding to basic facts and solve problems by rote algorithmic methods. For example, alternative conceptions dealing with chemical equilibrium have often been seen as a result of applying the basic rules of Le Châtelier’s principle without a conceptual understanding of what is going on at the submicroscopic level (Garnett et al., 1995; Quílez, 2004). It is important then, for teachers to avoid rote methods, and teach for deep conceptual understanding.

Bodner theorized that alternative conceptions also stem from the experiences that children have with the outside world, including the media. An example that he provided was how The Flintstones may have put the idea in children’s minds that dinosaurs and humans existed at the same time (Bodner, 1991). In addition, the oversimplifications made by teachers to teach concepts for the first time may lead to alternative conceptions. Sometimes, many models of increasing difficulty are presented for a concept, and students do not see the limitations of the applications of each model. This happens, for example, in the case of acid-base chemistry (Garnett et al., 1995). It was also found that students often had inadequate prior knowledge, which lead to difficulties in learning new concepts and the formation of alternative conceptions. For example, without a good understanding of reactions and stoichiometry, alternative conceptions in the area of equilibrium were probable (Garnett et al., 1995; Skelly & Hall, 1993).

In most cases, texts drive curriculum. Textbooks have often contained language whose meaning does not match with scientific definitions (Coll & Treagust, 2001). Textbooks, also, have not always made a distinction between the individual and bulk properties of matter, and many of the diagrams contained errors with respect to representations regarding spacing, density, and the compressibility of liquids, as well as reactions taking place at the atomic level (Garnett et al., 1995; Taber, 2001). Texts may also provide only one or two similar examples, leading students to believe that what is stated is always the case. For example, an elementary science text that likens chemical reactions to baking a cake or cooking an egg would lead a student to erroneously assume that all chemical reactions are irreversible (Gabel, 1999). An examination of
different textbooks on the acids and bases unit showed that none of them explained the idea that different models were used to describe acids and bases, which model they were using when they gave examples, why different models were used together, or the limitations of each model (Drechsler & Van Driel, 2008). Another example from the unit on equilibrium is the treatment of Le Châtelier’s principle. Textbooks often present Le Châtelier’s principle as a section of the chapter on equilibrium and do not necessarily explain that it is a only guide to help predict the effects of a change in conditions on the position of equilibrium. Teachers who then use the textbook as a source of lesson planning (as new teachers often do) will carry out these errors in their classrooms, furthering alternative conceptions and confusion (Dreschler & Van Driel, 2008).

A recent study by Lemma aimed to correlate the alternative conceptions of teachers with the alternative conceptions of their students (Lemma, 2013), in order to determine whether the teachers were the source of alternative conceptions of their students. Lemma concluded that teachers were responsible for 90% of their students’ alternative conceptions. This data analysis did not consider the students’ past education, other outside sources of learning, or which teachers taught which students. It also utilized a simple linear correlation between the percent of students and teachers who had alternative conceptions on the same topics (Lemma, 2013).

Although uncertain of the legitimacy of the above methods and subsequent results, this writer found intriguing the notion of finding a way to determine if direct instruction of the alternative conceptions of teachers is the primary source of students’ alternative conceptions. To unequivocally determine which specific instructional techniques caused which alternative conceptions would be even more fascinating. The factors limiting the acquisition of this knowledge would be hard to overcome. It would be greatly difficult to determine all the sources of information available to each student. This would require detailed interviews, and even then, students most likely would not remember where and how they acquired each piece of information. Therefore, to reasonably attempt a study like this, one would have to (a) choose a topic for which students could not have gained knowledge in any other way besides direct instruction and then (b) assess prior conceptions of teachers and students at the beginning and end of the instruction of that topic to determine if new student alternative conceptions were formed. Only then, could a researcher (c) begin to look in detail at the specific methods of instruction used to teach students about that topic.

Measuring Alternative Conceptions

Studies that have been conducted to determine the chemical alternative conceptions of students, pre-service teachers, and in-service teachers have made use of a wide variety of instruments and measures, including interviews (Coll & Treagust, 2001; Treagust, Tan, Goh, & Chia, 2004), open-ended questions paired with interviews (Canpolat et al., 2006), conceptual knowledge exams (Bodner, 1991), concept-mapping (Gorodetsky & Gussarsky, 1986), think-aloud observations (Cheung, 2009b), open-ended question tests (Kolomç & Tekin, 2011), multiple choice tests (Hackling & Garnett, 1985), and two-tiered multiple choice tests with and without interviews (Chandrasegaran et al., 2007; Mulford & Robinson, 2002; Peterson et. al., 1989; Treagust, 1988; Voska & Heikkinen, 2000).

For example, the development of a two-tiered multiple-choice test, reported by Peterson, Treagust, and Garnett was based upon 33 propositional statements and concept maps concerning bonding (Peterson et. al., 1989). The first tier of each question was a multiple-choice question, and tested content knowledge. The second tier consisted of another multiple-choice question that
asked for the reason why the first-tier answer was chosen. The possible answers included common alternative conceptions held by students, identified during previously held student interviews. The test was improved during three pilot studies. The resulting fifteen-item Covalent Bonding and Structure Instrument was then given to a total of 243 students in grades 11 and 12 (chemistry was a two-year course) to gauge the prevalence of student alternative conceptions with respect bonding. The results, which showed a higher percent of correct answers on the first-tier questions, than on the second-tier questions, demonstrated that while the students were acquiring content knowledge, they were not developing an adequate conceptual understanding of the topic. From this test, the group identified thirteen chemical alternative conceptions regarding bonding concepts. For the 11th graders, the ideas that the shape of a molecule is due to equal repulsion between the bonds, and that covalent bonds are broken when a substance changes shape, were common alternative conceptions. For the 12th graders, the misconception that non-polar molecules form when the atoms in the molecule have similar electronegativities was common (Peterson et al., 1989).

In a similar style, the Chemical Concepts Inventory (CCI), a 22-item multiple-choice test developed and tested by Mulford and Robinson (2002), was created to test for alternative conceptions about topics across the chemistry curriculum. The CCI was developed by making a topic list using material found in a first semester college chemistry course, textbooks, articles outlining chemistry course content, an ACS exam, and articles on research describing alternative conceptions in chemistry. Topics included on the CCI dealt with often misunderstood topics: particulate nature of matter, properties of atoms, bonding, gases, liquids and solutions, conservation of mass and atoms, symbols, equations, stoichiometry, chemical reactions, heat and temperature, phase changes, and macroscopic versus atomic/molecular properties. A pilot inventory consisting of 18 open-ended questions was used to create the distractors, though the research report did not elaborate on who was tested. Eighteen graduate chemistry students and four science education researchers checked the final 22-question CCI for content, clarity and length. The CCI was then administered to 1418 students as a pretest at the beginning of a semester, and as a posttest at the beginning of the next semester to 1553 students. A sample of 928 students put their ID number on both for comparison. Neither author taught the class, nor was there any attempt to address alternative conceptions during the class. The average pretest score was 45.5% (10.0/22). The average posttest score was 50.5% (11.1/22), even considering that the same questions were used. Of the 928 students that were compared further, the average increase was 0.94 points, with a range between -5 and +5 from the pretest. This increase, though it was less than 5%, was deemed statistically significant. Looking at the results, certain conclusions could be drawn. First, alternative conceptions were plentiful in this representative sample of students. Second, a traditional chemistry course resulted in only a small improvement in students’ conceptions (Mulford & Robinson, 2002).

Though it was originally designed to test the alternative conceptions of students, the CCI was found to be an acceptable way to test teachers’ alternative conceptions (Kruse & Roehrig, 2005). To this end, the CCI can inform professional development of in- and out-of-discipline teachers so that they may become more qualified to teach chemistry. A critique of the questions by Mulford and Robinson after the study was completed showed that some of the questions demonstrated only simple recall and not conceptual ideas. It was also suggested by the authors that simply knowing the nature of the alternative conceptions held by students (and by extension, teachers) is not enough to improve instruction. Teaching techniques must be used to help students construct the correct ideas on their own (Kruse & Roehrig, 2005).
A review and critique of the different methods used to identify alternative conceptions was prepared by Gurel, Eryilmaz, and McDermott (2015). They reviewed 273 studies and found that most common method used was interviews (53%), followed by open-ended tests (34%), multiple-choice tests (32%), multiple-tiered tests (13%), and other methods including concept maps, drawings, essays and the like (9%). Many studies utilized more than one technique. Overall, interviews were considered the most effective method for determining how people thought about concepts, though the method was open to interviewer bias and cumbersome data analysis. Two-tiered tests were more effective than multiple-choice tests due to the fact that each answer was justified by the respondent and paved the way to collecting in-depth reasoning from more participants than allowed for by interviews. A critique of two-tiered tests included the observations that (a) forced-choice items in the second tier may provide clues to the correct answers, (b) the wording of the second-tier questions could lead to incorrect analysis of alternative conceptions, and (c) two-tiered tests cannot always distinguish between lack of knowledge and alternative conceptions (Gurel et al., 2015).

Addressing Alternative Conceptions and Conceptual Change

There are ways that student alternative conceptions can be avoided. Students can be taught the underlying principles of physics needed to understand chemical concepts (Taber, 2001). For example, without the prerequisite knowledge of electric current, students will have trouble with electrochemistry. Teachers can also focus on molecules and ions rather than atoms, so that students do not develop the misconception that reactions happen at the atomic level. Bonding can be taught as an electrical concept, to decrease the incidence of anthropomorphism and allow the transfer of this concept to other types of bonding later. Careful and consistent use of terminology, coupled with teacher-provided definitions, would help constrain the alternative conceptions formed from the misuse of language (Bodner, 1991; Taber, 2001). White and Gunstone (1992) stressed the importance of exploring students’ ideas, and teaching for conceptual change. Educational experiences involving metacognitive approaches, including concept mapping, predict-observe-explain tasks, interviews, drawings, portfolios, and discussion, can be used to elicit information about student conceptions, and seem to be promising in their abilities to aid in the process of learning new concepts (Treagust, 2007). Along these lines, teachers have included in their instructional methods various techniques to capitalize on these main ideas and to make science more relative to their students. These techniques include demonstrations, classroom explanations, questioning, group and cooperative learning, lab work, and models. Common models used in the science classroom include concrete (material) models, mathematical models including equations, symbolic models including chemical formulas and equations, visual models including graphs and diagrams, gestural models, and verbal models including metaphors and analogies (Gilbert, 2004). However, the ability of a teacher to identify and address student alternative conceptions is based on his or her own content knowledge (Piquette & Heikkinen, 2005). Teachers, who are the source of knowledge in the classroom, are often unaware of the alternative conceptions that they possess because they do not often get opportunities to challenge those conceptions (Kruse & Roehrig, 2005). Therefore, the process of affecting conceptual change in themselves is overlooked, and classroom practice can be affected in terms of their instructional practices, the development of their pedagogical content knowledge, and even in their assessment development (Kwen, 2005; Talanquer et al., 2009).

Since constructivism demands that knowledge stems from experiences, then conceptual change can only occur when new concepts are created that better fit those experiences. Posner, et
al. (1982) described the four requirements for a conceptual change approach in the classroom. Learners must be (a) dissatisfied with their current knowledge. In other words, their current knowledge is shown to be ineffective with respect to answering or explaining a problem or concept (cognitive conflict). Then, a new concept presented must be (b) understandable and (c) plausible to the learner. Last, this new concept must be (d) fruitful in its ability to explain ideas and/or solve unfamiliar problems (Posner et al., 1982).

Vosniadou (1994) divided conceptual change into two forms: enrichment, or addition, of new knowledge to an already ingrained knowledge structure, and revision, or changes, to specific theories (e.g., ideas that describe properties and behavior or objects) and framework theories (e.g., global knowledge about the world). Revision is the more difficult type of conceptual change, required when new information does not match existing beliefs, presuppositions, or theories. Conceptual change is hardest when framework theories need to be revised, because these frameworks are based on understandable ideas that are backed up by everyday experiences, and they form the basis for other knowledge structures. An example provided by Vosniadou is the difference between learning that there are craters on the moon (an easy addition of knowledge to the specific theory that the moon exists) and learning that the Earth is a sphere (a difficult revision to the framework theory of how direction is organized in relation to a seemingly flat ground). Learning failures were characterized into inconsistencies, inert knowledge, and alternative conceptions. Inconsistencies occur when conflicting ideas are added to existing knowledge structures, often resulting in confusion when trying to explain those ideas. Inert knowledge is described as when differing ideas are stored in separate parts of the knowledge structure, and only used at specific times. An interesting example of inert knowledge is what Bodner called “domain specific knowledge.” He found that when organic chemistry students were asked to explain why acetylene was so reactive, they pointed to the triple bond in the molecule. Then, when students were asked in inorganic chemistry, why nitrogen was inert, they pointed to the triple bond as well, not realizing the discord between the two examples (Bodner, 1991, p. 11). Alternative conceptions, argued by Vosniadou, occur when students attempt to “interpret scientific information within an existing framework theory that contains information contrary to the scientific view” (Vosniadou, 1994, p. 46).

Over the past 25 years, there has been considerable research concerning the way students learn and which instructional strategies work best in the science classroom. Teachers can design classroom experiences so that students can construct their own knowledge. As Lorsbach and Tobin noted in 1992, a constructivist approach to learning has been recognized as more effective than a traditional lecture approach. The underlying concept of constructivism is that learners form their own knowledge as they connect new experiences to their prior knowledge. The real power of constructivism then, is that students are able to change their previously held conceptions if a new experience conflicts with their prior understanding of a concept (Lorsbach & Tobin, 1992). Also, teachers have included in their instructional methods various techniques to make science more relevant to their students’ lives. These techniques include demonstrations, explanations, questioning, group and cooperative learning, lab work, and models. Common models used in the science classroom include concrete (material) models, mathematical models including equations, symbolic models including chemical formulas and equations, visual models including graphs and diagrams, gestural models, and verbal models including metaphors and analogies (Gilbert, 2004).
2.3. Chemical Equilibrium, Rates of Reaction, and Le Châtelier’s Principle

Chemical equilibrium is a topic within the advanced chemistry curriculum that poses significant conceptual difficulties for students (Özmen, 2008). However, a complete understanding of chemical equilibrium is necessary to understand later concepts in the course, including acid-base chemistry and solubility (Tan, Treagust, Chandrasegaran, & Mocerino, 2010), and it is a concept that is important in other areas of science including physics and biology. The concepts of equilibrium are taught after reaction prediction and stoichiometry, and thus are in direct opposition to what has been previously learned in terms of directionality, completion, and macroscopic changes (Van Driel & Gräber, 2002). When studying chemical equilibrium, and what happens to a chemical system upon being disturbed from that equilibrium state, teachers can choose to focus on three general types of explanations: the equilibrium law (including the reaction quotient), Le Châtelier’s principle, and reaction rates (Tyson, Treagust, & Bucat, 1999). The most conceptual of these is the explanation utilizing reaction rates, since it requires the ability to visualize collisions of reactants and products on a submicroscopic level. However, the use of Le Châtelier’s principle is popular among teachers due to its algorithmic nature, often at the expense of a deep understanding of the concepts of equilibrium and its integration with reaction rates.

The research published in the literature presents consistent results: alternative conceptions pervade every aspect of equilibria studies. Alternative conceptions relating to the distinction between systems at equilibrium and those that are not, the dynamic nature of equilibrium, the meaning of the equilibrium constant, the interconnectedness of the forward and reverse reactions, vocabulary associated with equilibrium concepts, reversibility of reactions, reaction rates, the difference between rate and extent of reaction, the difference between moles and concentration, and the use of algorithms to solve problems (e.g., Le Châtelier’s principle) are found consistently in the literature (Bergquist & Heikkinen, 1990; Gorodetsky & Gussarsky, 1986; Tyson et al., 1999; Wheeler & Kass, 1978). The following sections describe the plentiful research that exists regarding students’ alternative conceptions of chemical equilibrium, and the significantly smaller body of research describing teachers’ alternative conceptions in this area. As with research in other areas of chemistry, it has been found that teachers maintain similar alternative conceptions about this area to those that their students hold.

Students’ Alternative Conceptions Regarding Equilibrium and Reaction Rates

There has been a significant amount of research outlining the alternative conceptions of high school and college students with regard to chemical equilibrium and reaction rates (Akkus, Kadayıfci, & Atasoy, 2011; Bain & Towns, 2016; Banerjee, 1991; Bergquist & Heikkinen, 1990; Garnett & Hackling, 1984; Gorodetsky & Gussarsky, 1986; Hackling & Garnett, 1985; Huddle & Pillay, 1996; Kousathana & Tsaparlis, 2002; Pedrosa & Dias, 2000; Quilez, 2004; Quilez-Pardo & Solaz-Portolés, 1995; Voska & Heikkinen, 2000; Wheeler & Kass, 1978). Table 1 shows some of the alternative conceptions found in the literature. Students’ alternative conceptions about equilibrium have been shown to pervade every area of the chemical equilibrium construct, including the approach to equilibrium, characteristics of equilibrium, changing equilibrium conditions, and the addition of a catalyst. Representative samples of these studies are outlined below.
<table>
<thead>
<tr>
<th>Approach to Equilibrium</th>
<th>Changing the Equilibrium Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>• rate(_f) increases as reaction proceeds</td>
<td>• when equilibrium is re-established, rates are equal to those at initial equilibrium</td>
</tr>
<tr>
<td>• rate(_f) = rate(_r) always</td>
<td>• K changes with changes to concentration or volume</td>
</tr>
<tr>
<td>• reaction(_f) completes before reaction(_r) begins</td>
<td>• K is independent of temperature</td>
</tr>
<tr>
<td>• reaction yield and rate are the same concepts</td>
<td>• LCP always applies; increases rate of favored reaction; decreases rate of opposing reaction</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Characteristics of Equilibrium</th>
<th>Role of a Catalyst</th>
</tr>
</thead>
<tbody>
<tr>
<td>• there are simple arithmetic relationships between [reactants] and [products]</td>
<td>• affect the rate(_f) and rate(_r) differently</td>
</tr>
<tr>
<td>• at equilibrium rate(_f) will be faster or slower than rate(_r), based upon K</td>
<td>• catalysts increase the speed of molecules</td>
</tr>
<tr>
<td>• equilibrium is not dynamic</td>
<td></td>
</tr>
<tr>
<td>• reversible reactions go to completion</td>
<td></td>
</tr>
<tr>
<td>• oscillating behavior and concentrations</td>
<td></td>
</tr>
<tr>
<td>• at equilibrium, rate(_f) = equals rate(_r) = 0</td>
<td></td>
</tr>
<tr>
<td>• each side of the reaction is separate</td>
<td></td>
</tr>
<tr>
<td>• the larger the K, the faster a reaction occurs</td>
<td></td>
</tr>
<tr>
<td>• the smaller the K, the faster a reaction occurs</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Some alternative conceptions regarding equilibrium and reaction rates.

In their 1984 study, which has served as the foundation for many subsequent studies, Garnett and Hackling aimed to identify alternative conceptions that students held about chemical equilibrium (Garnett & Hackling, 1984). Based on twenty-six propositions concerning equilibrium, an interview instrument was developed to ask probing questions of high school students, and a pencil and paper test was administered to college students. Garnett and Hackling found that students had a poor understanding of equilibrium concepts. Major alternative conceptions held by students were that (a) reaction rate of the forward reaction increases as the reaction approached equilibrium, (b) that the concentration of the reactants equal the concentration of the products at equilibrium, (c) when a disruption to equilibrium occurs, the rate of the favored reaction increases but the rate of the opposing reaction decreases, (d) the equilibrium constant changes if the concentration of one of the chemical species is changed, and (e) catalysts affect the forward and reverse reactions differently. Overall, both groups of students showed a poor overall understanding of the equilibrium condition. Garnett and Hackling posed some reasons for the alternative conceptions they found. In the case of increasing rates for forward reactions, they suggested students’ experiences with reactions that take some time to begin, such as the reaction between hydrochloric acid and magnesium, which lags until the oxidized coating of magnesium is dissolved. They also suggested that since so much emphasis was placed on stoichiometric relationships during earlier units, students assumed simple mathematic relationships between reactants and products at equilibrium. Last, since reactions
that demonstrate reversibility are rare in introductory chemistry, students are reasonably unable to consider the forward and reverse reactions separately in an equilibrium reaction (Garnett & Hackling, 1984).

Akkus, Kadayifci, & Atasoy (2011) developed a two-tier multiple-choice assessment based upon the 1984 study by Garnett and Hackling, and administered it to 102 tenth grade students. They identified 25 alternative conceptions similar those identified in the study by Garnett and Hackling (as well as other studies), and concluded that the students had a poor understanding of chemical equilibrium. Voska and Heikkinen (2000) developed a 10-item, pencil and paper, two-tier test to measure the alternative conceptions shown by 95 university students when solving equilibrium problems where Le Châtelier’s principle was required. In addition, nine students as a representative sample were interviewed. The most widely held alternative conceptions found by Voska and Heikkinen (2000) dealt with the effects of temperature changes on equilibrium and represented half of the alternative conceptions identified.

Research by Pedrosa and Dias (2000) studied how alternative conceptions regarding equilibrium could be caused by the use of language in four chemistry textbooks. The research supported the idea that the language used in the texts contributed to student alternative conceptions, and some sections of the texts were inaccurate or ambiguous. Words and phrases that were found to be problematic were “the reaction” (when reactions, or equilibrium system was intended), “shifts,” “reversible reaction” (instead of simultaneous reactions occurring at equilibrium), and “insoluble salts.” It was also noted that early in their chemistry instruction, students see “chemical changes” as irreversible, and “physical changes” as reversible, further complicating the study of equilibrium (Pedrosa & Dias, 2000).

Bain and Towns (2016) analyzed 34 studies regarding the teaching and learning of kinetics. They summarized alternative conceptions relating to five enduring understandings: chemical change measured as a function of time, dependence of reaction rates on concentrations of reactants and temperature, reactions proceeding through elementary reactions/mechanisms, the requirement of collisions, minimum energy, and proper orientation for reactions to occur, and the role of catalysts. Also reviewed and discussed were the integrated nature of kinetics and equilibrium, and the common theme that students had significant difficulty with graphical and visual representations (Bain & Towns, 2016).

**Teachers’ Alternative Conceptions Regarding Equilibrium and Reaction Rates**

As with all areas of chemistry, it has been found that teachers maintain similar alternative conceptions to their students with respect to equilibrium and reaction rates, though relatively few studies have been reported on this topic, and the majority of these have focused on pre-service teachers (Azizoglu et al., 2006; Banerjee, 1991; Canpolat et al., 2006; Dindar, Bektas, & Çelik, 2010; Pinarbası et al., 2009; Quílez, 2004) as opposed to experienced teachers (Cheung, 2009a; 2009b; Cheung, Ma, & Yang, 2009; Kolomuç & Tekin, 2011; Quílez, 2004; Quílez-Pardo & Solaz-Portolés, 1995). All of the studies found that teachers, like students, misinterpreted the equilibrium condition and overused Le Châtelier’s principle to solve problems algorithmically.

One such study by Canpolat et al. (2006) determined the conceptions relating to vapor pressure of 70 third-year prospective science teachers in Turkey, who had already taken courses in general, organic, and analytical chemistry. Using a five-question open-ended test, they found that 57% of the student teachers studied provided only a partially correct definition of vapor pressure that did not include the concept of an equilibrium state. Interviews confirmed the lack of this concept knowledge. The alternative conceptions that vapor pressure is dependent on the
volume of the vapor, and that vapor pressure changes with the volume of the liquid, were seen in more than half of the responses (57% and 53%, respectively). The misconception that different liquids boiling at the same atmospheric pressure have different vapor pressures was even more widely held (62%). This last misconception demonstrated how the relationship between vapor pressure and the boiling point of a liquid was misunderstood or misinterpreted. There was no discussion in this report of an inquiry into what or when this concept was taught to the students, nor was the research compared to any other studies (Canpolat et al., 2006).

In a study of twelve secondary school chemistry teachers in Hong Kong, Derek Cheung found that none of them were able to correctly predict what would happen if a small amount of nitrogen gas was added to an equilibrium system containing hydrogen, nitrogen and ammonia gases in a system contained by a movable piston (Cheung, 2009b). Though the teachers had, on average, 8.8 years of experience, they tended to use Le Châtelier’s principle to predict an incorrect shift in the equilibrium position. Since Le Châtelier’s principle is an oversimplification of a phenomenon, it does not apply in all cases. The problem that the chemistry teachers were provided with was one in which a volume change as well as a reaction quotient needed to be considered. Cheung was able to observe the over-reliance on Le Châtelier’s principle only because his study made use of a think out-loud protocol, where he was able to listen to each teacher choose to apply the principle. Though the sample size for the study was small, it did expose the cognitive process for these teachers and opened the door for similar studies about other types of problems (Cheung, 2009b).

Kolomuç and Tekin (2011) reported on the use of a nine open-ended question test to determine teachers’ knowledge of the concept of reaction rates. Including questions about reaction-time graphs, reaction mechanisms, activation energy, and the relationship between rate and enthalpy, their study tested 70 experienced teachers. Kolomuç and Tekin found that for each question, a sizable percentage (up to 30%) of the answers contained specific alternative conceptions of the rate concept, similar to those of students.

Cakmakci (2010) conducted a study regarding the kinetics concepts of 108 secondary chemistry students, as well as chemistry teacher trainees in their first (n=48) and third (n=35) years, after which kinetics is studied in Turkey. Data were collected through an 11-item open-ended test as well as interviews with 24 of the participants. Questions dealt with both recalling information as well as applying it to graphing and explanations. The group identified a total of 11 alternative conceptions, including ideas relating to how reaction rate changes as a reaction progresses, the effect of temperature on the rates of reactions, and the effect of a catalyst on the rate of a reaction (Cakmakci, 2010).

Integration of Equilibrium and Reaction Rates

As noted by Bain and Towns (2016), chemical equilibrium and kinetics are integrated topics, and students often get confused when they try to combine the concepts of these two areas of chemistry. Examples of the overlap between the two topics are (a) the relationship between the forward and reverse reaction rates in a system approaching equilibrium, (b) the idea that equilibrium is reached when the opposing reactions occur at the same rate, (c) the dynamic nature of equilibrium existing because the rates of the forward and reverse reactions are not zero, and (d) the effect of a stress to a system at equilibrium on the rates of the forward and reverse reactions. Many of the studies that have aimed to identify the alternative conceptions of students and teachers with respect to chemical equilibrium have included reaction rate concepts on their
assessments (Akkus, Kadayifci, Atasoy, & Geban, 2003; Bilgin & Geban, 2006; Hackling & Garnett, 1985).

Concentration and Rate Graphs

The ability to draw and interpret graphs of concentration versus time and rate versus time for reversible reactions are important measures of conceptual understanding for the topics of equilibrium and kinetics. Wheeler and Kass (1978) suggest that lessons including concentration versus time graphs would be beneficial for helping students overcome the alternative conceptions regarding chemical equilibrium. Of concern, then, is the general finding that chemistry students and teachers have difficulty with visual representations of concepts. For example, Kolomuç and Tekin (2011) analyzed the responses of 70 experienced chemistry teachers on a 9-question, open-ended test. Of these questions, two dealt with graphing rate versus time for a chemical reaction. 32% of the graphs drawn by the participants contained alternative conceptions, and 24% of explanations of graphs provided contained alternative conceptions (Kolomuç & Tekin, 2011).

Though students and teachers have difficulty with graphing, it can be used to affect conceptual change. In a study by Hameed, Hackling, and Garnett (1993), students were exposed to a computer-assisted instructional package after being given a pretest on chemical equilibrium concepts. The program was based upon Posner’s requirements for conceptual change and worked in three phases. First, students were asked to predict what would happen to a system at equilibrium when conditions are changed. Next, the program showed graphically what actually happened to the system when the change was made. Third, the students’ responses were displayed to create cognitive conflict. Next, an explanation of the scientifically accepted answer was provided. Last, the program allowed the participants to apply the concept that was just covered in a new situation. The program covered many aspects of chemical equilibrium, including forward and reverse reactions, equilibrium constants, equilibrium concentrations and rates, effect of catalysts on rates, and Le Châtelier’s principle. The participants were given a posttest directly after treatment as well as one month later. Some of the participants were also interviewed before and after the treatment program. Results of the study showed that the students’ performance on the posttest was significantly higher than the pretests. When each student’s answers were analyzed for the correction of each misconception, it was found that, for 10 of the 16 alternative conceptions identified in the pretest, over 50% of them were corrected on the posttest. Graphing, then, can be a powerful part of instruction and conceptual change (Hameed et al, 1993).

In textbooks, graphs of concentration and rate as they relate to chemical equilibrium are generally limited to depicting the approach to equilibrium from the mixing of reactants. Concentration and rate graphs, presented together, which depict changes to the equilibrium condition, have not been widely addressed in texts or in the literature, though a few websites have been published from countries outside of the United States (e.g., Dynamic Science Education, 2019).

2.4. Framework for the Study

Chemistry teachers have a particularly challenging job because the concepts in chemistry are often abstract, complex, and difficult to visualize by students. To that end, a teacher must have thorough subject matter knowledge, excellent subject matter structure and well-developed
pedagogical content knowledge. The next sections focus on subject matter knowledge, pedagogical content knowledge, and subject matter structure.

**Teachers’ Subject Matter Knowledge**

The ability of a teacher to identify and address student alternative conceptions is based on his or her own chemistry content knowledge (Piquette & Heikkinen, 2005). Also, since conceptions that teachers hold may be passed on to students (Cheung, 2009a; Kolomuç & Tekin, 2011; Taber & Tan, 2011), it is important to understand how teachers think about and understand topics in chemistry, and how their teaching strategies reflect this knowledge (Talanquer et al., 2009).

Before the ideas of constructivism and alternative conceptions were developed, teacher education was about general knowledge, rather than subject-specific knowledge. In 1986, Lee Shulman proposed that subject matter knowledge was the “missing paradigm” in teacher education and research (Shulman, 1986, p.6), and that teachers are professionals and therefore have a specialized knowledge base. First separating subject matter knowledge into three categories (subject matter content knowledge, subject matter pedagogical knowledge, and curricular knowledge, Shulman later reorganized these ideas into seven knowledge base categories, including (a) content knowledge, (b) general pedagogical knowledge, (c) knowledge of curriculum, (d) pedagogical content knowledge, (e) knowledge of learners, (f) knowledge of educational contexts, and (g) knowledge of educational purposes, philosophy, history, and values (Shulman, 1987). The idea of pedagogical content knowledge (PCK, discussed below) was separate from subject matter knowledge, and spurred a vast amount of discussion in the literature about whether they were two separate domains of knowledge, or two components that are so fundamentally connected that they cannot be considered separately. Vanessa Kind reviewed the opposing schools of thought on PCK and separated the interpretations into two models: the “transformative” model and the “integrative” model. Those who think of subject matter knowledge as distinct from PCK believe, in essence, that subject matter knowledge is “transformed” by PCK into a new type of teaching knowledge. Those who subscribe to the integrative model believe that the two types of knowledge are non-distinguishable, and that PCK encompasses both subject matter and pedagogy (Kind, 2009). For the purposes of the current study, this researcher subscribed to the transformative model, focusing only on the subject matter knowledge and structures of teachers, assuming that these would be transformed by their PCK and their knowledge of students to affect classroom practice and ultimately, student understanding.

Arzi and White conducted a 17-year, longitudinal study to assess how teachers’ knowledge changed over time. Collecting interview, curricula, and classroom observation data from (a) the last two years of their teacher training and (b) 17 years later, Arzi and White made several findings relevant to the current study. First, they found that knowledge change took on multiple types, including the forgetting of unused knowledge and limited accumulation of new knowledge, but improved understanding, increased knowledge structure reorganization, and integration. Second, they found that teacher development was based upon initial knowledge and interest, and more likely to occur when teachers were teaching within their chosen field of study. Third, they found that the requirements of the teachers’ training program were the most powerful indicator of teacher knowledge (Arzi & White, 2008).

Focused on the idea that a teacher’s content knowledge as well as his or her knowledge of content representations will certainly affect learning in a science classroom, Talanquer et al. (2009) compiled a review of research in the area of prospective chemistry teachers’ subject
matter and pedagogical content knowledge. Noting that there had been very little research on this important topic, especially with respect to secondary teachers, the goal of the article was to (1) generalize what is known about teachers and apply that knowledge to chemistry teachers, (2) identify gaps in research dealing with chemistry teachers’ knowledge, and (3) to outline research that must be completed for current knowledge in this area to be expanded (Talanquer et al., 2009). With respect to content knowledge, they summarized that prospective science teachers had a weak conceptual understanding of the subject matter and demonstrated the same types of alternative conceptions that students did. They did not get this knowledge from their college courses, and research showed that teachers’ knowledge of their subject matter had affected the process of instruction. Also, prospective as well as experienced teachers generally held naïve ideas about the nature of their discipline. Teachers with these beliefs passed them on to students. For example, teachers who held positivist views of science often chose structured labs, reinforcing the idea for students of a strict scientific method. Physics teachers who thought of their course as calculations-based tend to teach problem solving. Those who thought of it as a way of describing the natural world tended to teach more conceptually. With respect to content representations, Talanquer et al. reported that the ability of a teacher to transform knowledge into effective representations definitely affected what went on in a classroom. Models, analogies, examples, etc. were important to student learning, and developed in response to experience, reflection, and awareness of the research done in this area. Mentors played a large role in this development as well. The group concluded that further studies are needed to show how subject matter knowledge affects teaching and learning, as well as teachers’ ability to gather information about their students’ knowledge (Talanquer et al., 2009).

**Pedagogical Content Knowledge (PCK)**

Having content knowledge free from alternative conceptions is an important goal for teachers. However, the experienced teacher is aware that content knowledge is not enough to render teaching successful in the classroom. The specific modes of instructions that teachers use to transfer their content knowledge to their students falls under the category of pedagogical content knowledge (PCK), an idea fully developed by Lee Shulman in 1986. According to Shulman, pedagogical content knowledge is

…the most useful forms of representation of…ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations – in a word, the ways of representing and formulating the subject that makes it comprehensible to others…a veritable armamentarium of alternative forms of representation, some of which derive from research whereas others originate in the wisdom of practice (Shulman, 1986, p. 9).

In short, Shulman described PCK as the knowledge that is used to transform content knowledge into information that is understandable to students. Importantly, PCK includes the ability of a teacher to understand the likelihood of alternative conceptions that students have about each topic and determine which teaching strategies will bring about conceptual change. The development of teachers’ PCK begins, hopefully, during their training, and continues actively throughout their careers.

In short, the development of pedagogical content knowledge involves education, experience and reflection. There has been a significant amount of research looking at the development of a
teacher’s PCK during their pre-service education, usually looking at the development of PCK within a particular topic being studied in a teacher education program and its application in the student teaching experience. A representation of this type of study can be seen in Van Driel, De Jong, and Verloop’s study of pre-service teachers as they learned techniques to teach chemical concepts on the micro- and macro levels. It was found that the teaching experience – being in the classroom – was the most important part of the development of PCK with respect to this topic. Student questions, correcting exams, reading assignments, and observing student behavior during lessons increased teachers’ PCK. The workshop gave the basic understandings of the concepts that the teachers needed to focus upon. Meetings with mentors also influenced PCK for these teachers (Van Driel, De Jong, & Verloop, 2002).

Less research has been done on the continued development of PCK in experienced teachers. Drechsler and Van Driel studied teachers who had attended a professional development workshop dealing with the alternative conceptions of students with respect to acid-base chemistry. They interviewed those teachers two years later, to determine how their teaching changed as a result of the workshop, as well as from the start of their careers (Drechsler & Van Driel, 2008). When the teachers reflected on the development of their teaching skills over time, the most common reasons provided for a change in teaching practice was reflecting on student difficulties, including listening carefully to questions and statements during class, having students evaluate lessons, and reflecting on examination answers. Discussion with colleagues was another way of developing their PCK. Some teachers expressed that they were exposed to research, or participated in courses or workshops, though mostly at the beginning of their careers. Later in their careers, the teachers felt they lacked time, and did not need workshops as much. A common method used by these teachers was reflecting on their own lessons, to feel whether they had done it “right.” A very telling part of the study occurred as teachers were asked about the effect of the workshop on the teaching of acids and bases. Some of the teachers remembered the workshop and used it to modify their teaching, while others could not even remember what the workshop covered (Drechsler & Van Driel, 2008). This shows how the development of PCK is unique for every teacher, and probably cannot be reduced to a set of propositions that you can learn in a pre-service course.

Of course, not all PCK is developed from workshops and carefully structured professional development opportunities. Much PCK must be developed by teachers on their own with the help of books, internet resources, and curriculum materials. Many sources provide teachers with materials and suggestions for presenting specific topics in class and discovering alternative conceptions of students (Krieger, 2012; Taber, 2002a, 2002b; White & Gunstone, 1992). Teachers modify these materials to suit their needs and the needs of the specific learners in the class. Last, though not common, would be the use of research articles to inform the development of a teacher’s PCK. The availability of research articles on the internet could be helpful to teachers trying consciously to develop their PCK. Sometimes, however, this is not as easy as it seems.

A teacher in the study by Drechsler and Van Driel made an interesting statement regarding his use of research to develop PCK. He said that he had read research articles on science teaching, but found the ideas difficult to implement, and therefore abandoned this course of professional development (Drechsler & Van Driel, 2008). There is a wide gap between research and teaching that must be closed to allow teachers to take full advantage of the research which is conducted for the purpose of informing the development of PCK. In a recent publication, Onno De Jong wrote about this research-teaching gap, detailing the frustration of researchers who felt their work was not affecting practice, and the frustration of teachers, who felt the research was
not practical enough for their use. Teachers cited lack of time as a reason for the research-
teaching gap. They did not have enough time to read and translate research into practice. 
Researchers said they must publish in high-ranking journals commonly unread by teachers. 
Researchers assumed that teachers could understand their reports, and teachers assumed that 
researchers should be able to apply their research to solutions to common classroom problems. 
There was a “top-down” effect as well. Researchers carried out studies that were used to inform 
policy and curricula, which were then given to the teachers to implement, further alienating 
researchers from teachers. Last, research could get very general, which was not helpful to the 
classroom teacher with specific content issues trying to develop PCK. The common feeling 
between researchers and teachers was that there was not enough collaboration between them (De 
Jong, 2005). Suggestions for closing the gap include creating workshops to teach teachers how to 
handle the literature, engaging teachers in their own research activities, engaging researchers in 
teaching activities, having researchers publish in more accessible media for teachers, and 
increasing communication and collaboration between researchers and teachers (De Jong, 2005). 
It is problematic that this gap between research and teaching exists, because powerful studies 
done on methods of instruction, such as the use of analogies on classroom learning, are often 
going unnoticed by classroom teachers.

**Conceptual Framework for the Study – Subject Matter Structure**

The conceptual framework for this study is built around the idea of teachers’ subject matter 
structure (Abd-El-Khalick, 2006; Gess-Newsome & Lederman, 1993; Lederman, Gess-
Newsome, & Latz, 1994), which is how teachers understand and integrate the concepts they 
teach. This study will explore how teachers understand and integrate the topics of chemical 
equilibrium and reaction rates. Characterizing subject matter structure is difficult due to the 
varying definitions and interpretations of similar knowledge domains found in the literature. For 
this study, subject matter structure will be interpreted as being composed of seven areas that 
come together to integrate knowledge in the minds of teachers. Most importantly, a teacher must 
have a good understanding of chemical equilibrium and reaction rates (subject matter 
knowledge), since there is no way to integrate concepts if the knowledge of individual concepts 
is not well understood. Knowledge of the different levels of representation in chemistry is 
necessary as well, since full explanations of equilibrium include the behavior of particulate 
matter, chemical equations, and macroscopic changes. Understanding what students need to 
know (knowledge of the curriculum) guides a teacher in determining what is important to teach, 
as is the teacher’s own beliefs about efficacy and the importance of integrating the topics. Also 
feeding into a teacher’s subject matter structure is how concepts are presented in the textbook, 
the experience of the teacher, and the teacher’s own alternative conceptions about the topics. In 
order to achieve the goals of student understanding, teachers must combine their pedagogical 
content knowledge, their knowledge of their students, and their subject matter structure into their 
classroom practice. A representation of this authors interpretation of how these components 
affect a teacher’s subject matter structure is shown in **Figure 1**.
It is the difficult task of the chemistry teacher to try to combat the difficult nature of chemistry by considering the alternative conceptions of their students, being mindful of and correcting their own alternative conceptions, and developing their subject matter structure and pedagogical content knowledge. This research will explore teachers’ conceptions of chemical equilibrium in terms of reaction rates. The study is framed, therefore, by how teachers think about chemical equilibrium conceptually, and their reasoning about changes to the equilibrium condition. Thus, the ideas of constructivism, alternative conceptions, subject matter knowledge and structure, and conceptual change play roles in how this research will be interpreted.
Chapter 3

Methods

3. Overview of the Study

The purpose of this study was to investigate experienced chemistry teachers’ conceptions about chemical equilibrium as it relates to reaction rates. Thirteen teachers of advanced high school chemistry who had five or more years of experience completed an online version of the Chemical Equilibrium Concepts Test [CECT] (Hackling & Garnett, 1985), and participated in interviews containing graphing tasks. Through the data collected, information about each teacher’s alternative conceptions regarding equilibrium and reaction rates was obtained, as well as information about how they considered that the topics were integrated and how they portrayed the relationship in their classrooms. This chapter discusses the methods used to answer the research questions, including the methodological framework for the study, preliminary work leading up to the study, pilot studies, and the main data collection process.

3.1. Methodological Framework for the Study

Though a quantitative approach generates a large amount of data that would be generalizable to a larger group of teachers, a qualitative approach delivers more useful data in terms of understanding the perspectives of individual teachers and exploring their conceptions in detail (Libarkin & Kurdziel, 2002). This is further supported by comparing studies that have been completed in the areas of equilibrium. In those that utilized a primarily quantitative approach to discern the conceptions of students (e.g., Peterson et al., 1989; Voska & Heikkinen, 2000) it was found, through interviews with a small sample of participants, that participants could sometimes answer the pencil and paper questions, including the explanatory tier of two-tier questions, correctly without actually having the correct conceptions of equilibrium. It required the qualitative methods to discover the actual ideas of these participants regarding equilibrium. Very rich data that was directly tied to teachers’ alternative conceptions were collected in studies that utilized primarily qualitative methods, such as think-aloud protocols and interviews (e.g., Cheung, 2002b; Garnett & Hackling, 1984). For this study, a similar qualitative approach was used to generate the rich data needed to thoroughly appreciate patterns with respect to teachers’ understandings of chemical equilibrium and their ability to explain the concepts using reaction rates. An interview guide approach was used to structure interviews while allowing for discussion when it arose (Patton, 2002, p. 343). Additionally, interviews about instances and events would likely uncover participants’ recognition and interpretation of chemical concepts, and so this approach was used (White & Gunstone, 1992, p. 65).

A collective case study method (Creswell, 2013, p.99) was employed to provide a detailed description of each teacher’s conceptions of chemical equilibrium, reaction rates, and how they are integrated. Each teacher represented a case in the study, for a total of 13 cases containing interview and CECT data. A case study methodology was appropriate to purposefully sample
cases and explore the different perspectives of teachers of differing teaching experiences with respect to these topics. A case study approach employs different techniques to obtain and triangulate data and allows for the detailed analysis of the themes that emerge during the study of the cases (Creswell, 2013, p. 101).

3.2. Preliminary Work

Delphi-Like Study

A construct for chemical equilibrium was delineated by Hackling and Garnett (1985) and was composed of a list of twenty-six propositions concerning equilibrium. The propositions are reproduced in Appendix A. The propositions are true statements regarding equilibrium such as,

After equilibrium has been established, the concentrations of all the species remain constant with time.

or

After equilibrium has been achieved, and the volume of the system is decreased (but the temperature remains unchanged), the concentrations of all gaseous species in the system will instantaneously increase.

In order to establish whether the propositions were still relevant more than thirty years after they were defined, a Delphi-like study was conducted. A Delphi study is a method used to obtain consensus from a group of experts on a specific topic under study using a series of initial and follow-up questionnaires. Other materials, including a series of textbooks, lecture notes, syllabi, etc., can also be considered in a Delphi study to gain consensus about current ideas about a subject. To begin this initial study, a review of seven commonly utilized advanced chemistry textbooks (Brown, LeMay, Bursten, Murphy, & Woodward, 2012; Chang, 2010; Green & Damji, 2007; Hill, Petrucci, McCreary, & Perry, 2005; Masterton & Hurley, 2009; Spencer, Bodner, & Rickard, 2012; Zumdahl & Zumdahl, 2010) was conducted to determine if each of the propositions were addressed within the chapters for chemical equilibrium and kinetics, and if (and/or how) they were related to each other. Next, a similar review of the Advanced Placement (AP), International Baccalaureate (IB), and Advanced-Level (A-Level) Chemistry syllabi was conducted, along with a few college-level chemistry course syllabi that could be found online. The Advanced Placement (AP) Program, offered by the College Board in the United States and Canada, is a college-level program administered at the high school level (The College Board, 2014). It culminates with an examination in May of each year, which may allow students to obtain college credit and advanced standing in college for satisfactory work. Similarly, the International Baccalaureate (IB) Program, offered in many countries, allows students in high school to pursue college-level study that is internationally recognized (International Baccalaureate Organization, 2014). The A-Level Chemistry Syllabus, developed by Cambridge International, is an advanced curriculum designed for students in the United Kingdom interested in studying science at the university level. Its required papers are internationally recognized as qualifiers for college admission (Cambridge International, 2016).

Finally, a survey was delivered to four chemistry and chemical education experts. The survey allowed each expert to provide opinions on the current relevance of the original propositions and gave them the opportunity to comment on and add to the construct. The expert survey was
administered via the Qualtrics survey program, and vague or unclear comments were followed up via email.

Overall, the textbooks were consistent with the propositions. Most of the propositions could be found within the equilibrium chapters, though some were in the kinetics chapters. Notably, most of the textbooks did not discuss Le Châtelier’s principle as a function of rates of reaction, though these concepts were in the advanced syllabi. All but one of the participants in the main study utilized versions of textbooks examined in this Delphi-like study, and therefore, they were all working with textbooks that addressed the propositions. Generally, advanced chemistry textbooks follow a prescribed order. In all of the texts used by the main study participants and in advanced chemistry texts in general, the concepts of reaction rates are treated in a chapter regarding chemical kinetics, which is followed by a separate chapter on chemical equilibrium. The equilibrium chapter is, in turn, followed by individual chapters dealing with applications of chemical equilibrium systems, including acid-base chemistry and solubility equilibria. There does not seem to be a concerted effort on the part of the authors of these textbooks to bridge or integrate these topics.

For example, in the 8th edition of the book by Zumdahl, a popular text used by seven of the thirteen participants in the main study, the topic of reaction rates is not a common theme in the chapter on equilibrium. There are frequent statements about the forward and reverse reaction rates being equal at equilibrium, and a rate graph is shown for the approach to equilibrium when reactants are added together. Beyond this, rates are only mentioned casually, in the discussion of Le Châtelier’s principle, regarding what happens to an equilibrium system when a change to concentration is made. The text does not mention rates of reaction for changes in volume or temperature, utilizing instead the “shifting” language of Le Châtelier’s principle as the take-home message of these sections. This text also makes no mention of the relationship between the equilibrium constant and rate constants for the forward and reverse reactions for simplified, unimolecular reactions.

Two of the other texts used by a total of four of the main study participants (Chang, 10th edition and Brown & LeMay, 13th edition) do discuss the relationship between the equilibrium constant and rate constants. These two texts use this relationship to explain why the equilibrium constant does not change with concentration or volume changes, and why it does change with a change in temperature. Both texts also define the equilibrium state as equal reaction rates, though only Brown and LeMay’s book show a rate graph. Both texts do not mention rates of reaction at all when examining changes to the equilibrium condition except when the addition of a catalyst is discussed.

Upon a review of these and several other advanced chemistry textbooks as part of the preliminary study, it was found that the above is the general arrangement and content of the equilibrium unit. Equilibrium is described as the condition where the forward and reverse reaction rates are equal, but then the focus is on concentration for both the approach to equilibrium and for changes to the equilibrium state. Texts generally leave it to the teacher to make the connection between rate and concentration for their students. The 5th teacher’s edition of Perturucci’s text contains a sidebar that says, “Remind students that the rates of reaction (forward and reverse) are affected by the concentration of reactants.” Most texts simply overlook the integration of the topics. Some texts that were reviewed (Perturucci, 5th edition and Chang, 10th edition) had a promising section within the equilibrium chapter that suggested a relationship between kinetics and equilibrium, but only discussed the equilibrium constant as a function of rate constants.
The teachers generally followed their textbook, which, in all cases, separate the topics of chemical equilibrium and reaction rates. However, the fact that not one of the teachers suggested that the product under review in this study (NO₂) would dimerize in an equilibrium reaction to form N₂O₄, though this was a featured reaction in all of the textbooks used by the participants, suggested the possibility that they had not re-read their text in some time.

While reviewing the equilibrium chapters of textbooks, a chapter in an online textbook, *Chemistry for Use with International Baccalaureate* (Green & Damji, 2007), was a standout from the other texts surveyed. This text was quite specific in defining the relationship between reaction rates and equilibrium and was the only text to specifically state that Le Châtelier’s principle was just a “memory aid”, and that the reasons for the shifts in equilibrium position relied on what happened to the rates of reaction when a condition was changed. This text seemed more complete, and a student using this text would immediately be presented with how the two topics were related.

The syllabi themselves were more difficult to interpret due to lack of detail, however, most were like the texts with respect to the propositions. The Advanced Placement course outline, which is followed by most of the teachers in this study, does not specifically suggest the need for the integration of topics (The College Board, 2014). However, the College Board, which is the entity that administers the AP exam and is responsible for its syllabus, did publish a guide focused on chemical equilibrium in 2006 (*AP Chemistry 2006-2007 Professional Development Workshop Materials, Special Focus: Chemical Equilibrium*, 2006), in which all the propositions were included, as well as the expected objective of the integration of equilibrium with rate concepts.

The experts generally agreed with all the propositions. The only major discussion point was whether rates and equilibrium should be taught together. Although some felt that it would be too difficult for students to learn to integrate the concepts, agreement about its importance overshadowed that fear. Some quotes from the experts show this:

> While I’d like to have students understand how the rate of the reverse reaction is affected…reasoning pathway is complex. (Expert #2)

And,

> I think the rate difference would interfere with their understanding that the equilibrium constant remains the same. (Expert #2)

But,

> I would like to see rate…focused on as a separate sub topic (the relationship between kinetics and equilibrium...[in which] instruction is centered on the combination of these two chapters. (Expert #1)

And,

> …there has to be a way to lay out these concepts to students -- really focusing on the external stresses to the system, and how those stresses can impact the issues such as rates, concentrations, and rate constant. (Expert #4)

And,

> Students can often solve quantitative problems and wave their hands at Le Châtelier’s problems while having difficulty articulating the underlying concepts. (Expert #2)
It was also suggested that a focus of teaching chemical equilibrium should be on probing the alternative conceptions of students with respect to the propositions:

Students misconceptions of chemical equilibrium should be probed before teaching this topic. The conceptual understanding of chemical equilibrium is to try to avoid such kind of misconceptions. For example: At equilibrium, no reaction occurs; Equilibrium reactions go on until all the reactants are consumed; Forward reaction goes to completion before the reverse reaction starts; The concentrations of reactants and produces are equal at equilibrium. (Expert #3)

Interestingly, there was disagreement among the experts as to the accuracy of the rate-related propositions, demonstrating how some teachers might hold alternative conceptions about the relationship between equilibrium and reaction rates, and may not be able to explain the concepts of equilibrium through reaction rates. For example, Expert #4 disagreed with the proposition:

When equilibrium is re-established (after an increase in temperature disturbs an initial equilibrium state), the rate of the forward and reverse reactions will be greater than at the initial equilibrium.

commenting that they were having a tough time conceptualizing this...net rate of forward and reverse reactions should be zero.

Also of interest was the fact that in the original comments submitted online, as well as in the subsequent emails, the experts fell into speaking about student learning, though it was made clear at the beginning of the study that the research was specifically aimed at what teachers should be able to understand. This reiterates the overarching idea of this research – that teachers do not have as much of an opportunity to explore alternative conceptions, that they are the source of knowledge in the classroom, and that it is quite possible that their knowledge of concepts is taken for granted. The results of this Delphi-like study drove the research project in a new direction, since originally, the study concerned only the alternative conceptions of chemical equilibrium, and did not include the relationship between rates of reaction and equilibrium, and the ability of teachers to describe equilibrium in terms of rates of reaction.

The Delphi-like study provided evidence of construct validity (Campbell & Nehm, 2013) for the Chemical Equilibrium Concepts Test [CECT] (Hackling & Garnett, 1985), which was given to each participant in the Pilot Studies and in the Main Study, and was used to create the interview guide.

**Testing of the Chemical Equilibrium Concepts Test (CECT)**

The 47-item CECT has been used in several other studies and was found to have good reliability (Cronbach’s alpha = 0.87, Bilgin & Geban, 2006) when used with students. Here, the CECT was tested for its ability to distinguish between levels of expertise by administering the assessment online, via the Qualtrics survey platform, to a small sample of AP students, chemistry graduate students, MAT students, inexperienced chemistry teachers, and experienced chemistry teachers of all levels. Though the number of participants was not enough for a full-scale
statistical analysis of CECT results, it was enough to note that the questions often answered incorrectly by all levels of participants were those that described chemical equilibrium in terms of rates of reactions.

3.3. Pilot Studies

Two pilot studies were conducted, with a total of 4 teachers, to determine that the methods proposed for the study were appropriate for uncovering depth of understanding, that triangulation of data could be obtained, and to identify emerging themes from the research data.

In the initial pilot study, three teacher participants were first asked to participate in an interview composed of questions, explanations, graphing tasks, and a Predict-Observe-Explain (POE) activity. An interview guide approach was used, and after their initial answers to questions, participants were asked to explain their answers. Graphing tasks, which included drawing concentration versus time graphs and rate versus time graphs was completed during the parts of the interview dealing with the approach to equilibrium, changes made to the equilibrium state, and the addition of a catalyst. The Predict-Observe-Explain activity involved the change in glow stick light intensity with changes in temperature. Interviews lasted between 40 minutes and 115 minutes depending on the participant and were audio-recorded. After the interviews, participants were then asked to complete the CECT assessment, which was set up as an online survey, using Qualtrics survey software. Interview data were transcribed, read, and coded during three re-readings of the transcripts. For example, an “AC” (for “alternative conception”) coding was given to a statement suggesting that, upon reestablishing equilibrium after the addition of more reactant to a system, the rate of the forward and reverse reactions would be the same as they were at the previous equilibrium state. Other coding designations, which were ultimately used in the main study, are discussed in section 3.7.

After discussing the transcripts from the first pilot study with an expert in chemical education, several major changes were made to the design of the study. First, since it was observed that the results of the interviews impacted the results on the CECT, the procedure was changed so that participants would answer the CECT assessment first to get their initial ideas about equilibrium and reaction rates before the graphing tasks of the interview caused any conceptual change. Also, a minimum waiting period of five days was added between the completion of the CECT and the interview to ensure that the questions did not affect the interview responses. Third, the interview was re-structured to specifically glean an initial response, an explanation response, and a graphing response to each question. Last, the POE activity was removed because it was found that it did not provide any useful information, and an extra question about the addition of water to a system at equilibrium was added instead.

The second pilot study was completed to ensure that the changes made to the interview guide produced the desired information. The participant was a high school teacher who has taught high school chemistry at different levels (including AP). It was found during this interview, that the revised interview guide would elicit an initial response, an explanation response, and a graphing response to each question. Last, the POE activity was removed because it was found that it did not provide any useful information, and an extra question about the addition of water to a system at equilibrium was added instead.

The second pilot study was completed to ensure that the changes made to the interview guide produced the desired information. The participant was a high school teacher who has taught high school chemistry at different levels (including AP). It was found during this interview, that the revised interview guide would elicit an initial response, an explanation response, and a graphing response to each question. Finally, it was determined that having the teacher answer the CECT survey five days before the interview resulted in the ability to discuss the incorrect answers during the interview. Details of the pilot studies, including teacher demographics and a summary of the findings is provided in Appendix B.
3.4. Main Study

**IRB Approval, Informed Consent, and Protection of Human Subjects**

This study was submitted to and approved by the University’s Committee on Research Involving Human Subjects, project number 1126108-2. Each teacher participant was assured that their involvement in the study would remain confidential, and that he/she could choose to cease participation at any time. Informed consent was initially collected on the first page of the survey program providing the online assessment. Without choosing to consent, participants were not able to move on to the assessment questions. Each participant was also asked to sign a paper consent form before beginning the interview. A copy of the informed consent form, as well as the IRB approval letter is given in Appendix C. No private information was collected. The only personal information obtained at the time of the study was the educational and teaching background of the participants which, as publicly available information, could be verified.

Teachers’ identities were coded using a randomly generated 5-digit code. The teachers entered their codes into the Qualtrics survey program (which is encrypted with a digital certificate to safeguard information as it is sent to and from the university’s servers) to complete the CECT assessment. Their code was used with all study materials, including the file name for the digital audio recording of the interview, the interview guides, and the worksheets on which the drawing tasks were completed. Therefore, no study materials contained the names of the participants, and the only sources of the identities of the participants were the signed consent forms. Participants received their codes through emails, which the researcher deleted at the conclusion of the study. To further protect against a participant not deleting the emails containing their code, the participants were randomly re-labeled with a one-letter code, used in the analysis of the data and presented here. All paper study materials (consent forms and interview worksheets) were scanned to convert them into .pdf files so that paper copies could be destroyed at the conclusion of the study. Once the study was complete, the names of the participants were not retained and all study materials (assessments, recorded interviews, worksheets, consent forms, and interview guides) were downloaded onto a flash drive, password protected, and stored in a secure locked location. All study materials and data are to be destroyed after 5 years.

**Participants**

The study sample included 13 teachers who taught advanced (AP or IB) chemistry in public high schools in Nassau and Suffolk Counties in New York and held permanent or professional New York State certification in chemistry as their primary or secondary certification. For these certifications, a minimum of 5 years’ teaching experience was required. The participants for the study were recruited via publicly available email addresses, and their qualifications for the study were ascertained using the “Certification Lookup” tool provided by the New York State Education Department (New York State Department of Education, 2019b). A copy of the IRB-approved recruitment email is given in Appendix D. Emails were sent to 25 teachers at a time, until an appropriate sample of teachers were recruited. Of the 18 teachers who initially agreed to participate in the study, 13 completed both the assessment and interview and comprised the final study sample. One teacher was excluded from the study because she did not ultimately meet the inclusion criteria. One teacher completed the online assessment but decided to drop out of the study before the interview, thus excluding her from the study. Three other teachers agreed to participate but did not complete either component of the study. One of the teachers in the final
study group was a part of the New York State Master Teacher Program, designed to bring together “outstanding public-school teachers throughout the state who share a passion for their own STEM learning and for collaborating with colleagues” (SUNY, 2019).

Regarding teacher certification, the New York State Department of Education outlines the standards for teacher preparation programs on its website (New York State Department of Education, 2019a). The state requires its programs to consist of a “content core” and a “pedagogical core”. The “content core” requires a teacher to have major (or its equivalent) in a subject such as chemistry that provides the teacher with a knowledge base for assisting students in grades 7 through 12 in meeting the State learning standards for students. The “pedagogical core” is much more substantial, requiring thirteen different areas of knowledge, including sociological studies, working with students with disabilities, working with English language learners, instructional planning, use of technology, assessment, history and philosophy of education, the reporting of child abuse, violence, discrimination, and drug abuse, and a means to update knowledge, skills, and pedagogy. That last requirement, expressed one line of a detailed web page, is where a teacher preparation program is responsible for making sure that chemistry teachers (or teachers of any subject) have a depth of knowledge in their subject matter. However, when specific program requirements are listed, mention is made only about teaching and field experience (which, in New York, is minimally 40 days split between high school and middle school to be mentored by a teacher who is rated “effective” or “highly effective”, and 100 clock hours of field experiences related to coursework, respectively) and coursework that includes a study of adolescent learning and six semester hours of literacy skills study. Obtaining primary certification in a subject required a major in that subject (after 2004) or a major in science with at least a minor in the subject of certification (prior to 2004). With a primary or secondary chemistry certification, a teacher can teach any level of chemistry.

**Chemical Equilibrium Concepts Test**

The Chemical Equilibrium Concepts Test (CECT, Hackling & Garnett, 1985) was administered to each participant via the Qualtrics survey program. The assessment consisted of 47 multiple-choice and true-false questions about the chemical equilibrium system represented by the equation,

\[
2\text{NO}(g) + \text{Cl}_2(g) \rightleftharpoons 2\text{NOCl}(g) + \text{heat}.
\]

A copy of the CECT questions is provided in Appendix E. The survey also collected information about each participant’s educational and teaching background, including degrees obtained, certifications held, years of experience in the classroom, classes taught, and college chemistry courses completed.

**Interview and Graphing Tasks**

Teachers in the study were interviewed at least 5 days after they completed the CECT, in order to probe their understanding of the concepts within the construct of equilibrium. The location for the interviews and assessments was chosen for the convenience of the participants. The interview was structured to be similar to the CECT assessment, using a different chemical system,

\[
\text{N}_2(g) + 2\text{O}_2(g) \rightleftharpoons 2\text{NO}_2(g) + \text{heat}.
\]
Participants were provided with a worksheet and pencils. In the first part of the interview, they were asked to simply describe the equation, discuss whether it was an equilibrium reaction, and to explain their answers. They were then asked to describe, and subsequently draw, a representation of the system starting with one mole of nitrogen and two moles of oxygen (a) before any reaction occurred and (b) at equilibrium. They were asked to write the equilibrium expression for the reaction, and to describe what the expression meant to them. They were then asked to describe what it meant for the system if the equilibrium constant was large.

In the second part of the interview, the teachers were told that, for each of the events described, they would be asked to (a) predict what would happen to the concentrations of the reactants and products, or to the rates of the forward and reverse reactions, (b) explain why they believed their prediction was correct, and (c) graph the change in concentration or rate as equilibrium was established. In this part of the interview, instances included initial mixing of reactants, changes to concentration, temperature, and volume, addition of a catalyst, and the addition of water to the system at equilibrium. Teachers were asked to clearly explain what their graphs showed, in terms of where the new equilibrium occurred in relation to the initial equilibrium. A typical graph with discussion is shown in Figure 2.

Figure 2. Example of a graph and explanation given by participant K.

SG: Okay. So what does that show?

K: So, it's showing that the forward reaction, initially- Initially the rate increases, and then decreases and levels off. And the reverse does the opposite, where it decreases in rate, and then levels off to be the same rate as the forward reaction.

SG: Okay. And comparing the rate of the- the rate at equilibrium here, [referring to the final equilibrium] compared to the rate at equilibrium when we started, [K: Mmm-hmm.] is that higher? Lower? The same? I can't tell from your picture.

K: Here, they're about the same...And...I would say that they are about the same.

SG: Okay. When you say, 'about the same'...
In the final part of the interview, teachers were asked to discuss the teaching of equilibrium in their classrooms. They were asked what order they taught the topics of equilibrium and rates, and if (and how) they integrated the two topics.

A copy of the interview guide, phrased to elicit initial responses, explanation responses, and responses during the graphing tasks, is given in Appendix F. The interview guide reflects the equilibrium propositions delineated by Hackling and Garnett, alternative conceptions depicted in the literature, the CECT, as well as information gained in preliminary work. Interviews lasted approximately one hour and were audio-recorded and transcribed for analysis (see below).

**Debriefing**

Participants had the opportunity at the end of the interview to discuss with the researcher the information discussed about equilibrium and rates of reactions, so that they might take the information and graphing tasks back to their classrooms to include in their lessons. In addition, a copy of correctly drawn graphs was sent to each participant during the next academic year.

### 3.5. Analysis of Data

Interviews were analyzed using qualitative research methodologies. Before coding, each interview was transcribed, and read completely through while listening to the recorded interview. To verify the appropriateness of the codes used to analyze the data, several transcripts were discussed with an expert in chemistry education. The codes to be assigned were negotiated until an agreement about their usage was attained. Interviews were re-read and recoded in line with the research questions as described above. Version 8 of ATLAS.ti was initially used to analyze the data. The reliability of the coding for changes to the equilibrium system was established by having a colleague in the science education department complete the coding checklists (see Appendices 8.1 through 8.8) for the transcripts. The percent agreement was greater than 90% for the coding categories checked. In addition, the concentration and rate graphs drawn by the researcher, to which the participants’ graphs were compared, were checked by an expert in chemistry.

**Coding for Alternative Conceptions**

The goal of the first research question was to determine what alternative conceptions the teachers held about chemical equilibrium and reaction rates. To begin the analysis of the interview data, a list of *a priori* codes was defined for different levels of understanding, as previously been done in the research (see for example, Azizoglu et al., 2006; Haidar, 1997; Kolomuç & Tekin, 2011; Özden, 2009). The codes used were: Sound Understanding (“SU”), Partial Understanding (“PU”), Partial Understanding with a Specific Alternative Conception (“PU-AC”), Specific Alternative Conception (“AC”), and No Understanding (“NU”). Table 2 shows the codebook for these codes. These codes were assigned during a re-reading of the interviews. In order to receive an SU coding during the reading for alternative conceptions, all expected elements of a response must have been present. A PU coding was assigned if any element was missing, but no incorrect statements were made. PU-AC was assigned if some elements were correct, but an incorrect statement was made. If only the incorrect information was provided, an AC coding was assigned. No participants received a NU coding for any question, since all participants answered all questions. Requirements for the assignment of an “SU” code for each part of the interview are given in Appendix G. Once the interview data was
coded for any alternative conceptions the teachers maintained with respect to equilibrium and reaction rates, those alternative conceptions were analyzed for patterns with respect to each teacher’s educational and certification backgrounds as well as the frequency of the alternative conception among the study participants.

<table>
<thead>
<tr>
<th>Understanding Codes</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU</td>
<td>Response demonstrates an understanding of the concept and is fully complete.</td>
</tr>
<tr>
<td>PU</td>
<td>Response demonstrates an understanding of the concept but is incomplete.</td>
</tr>
<tr>
<td>PU-AC</td>
<td>Response demonstrates a general understanding of the concept, but a statement was made that indicates a specific alternative conception.</td>
</tr>
<tr>
<td>AC</td>
<td>Response indicates a specific alternative conception or response includes wrong or illogical information.</td>
</tr>
<tr>
<td>NU</td>
<td>Response indicates no understanding of the concept, indicates a lack of knowledge (“I don’t know”, etc.), contains irrelevant or unclear information, or no response was provided.</td>
</tr>
</tbody>
</table>

Table 2. Codebook for analysis of interview data for understanding of chemical equilibrium and reaction rates (Modified from Özden, 2009).

**Coding for Explanations of Chemical Equilibrium Concepts**

To align with the second research question, a new set of *a priori* categories was defined to explore the language used by the teachers to explain equilibrium concepts and changes to a system at equilibrium. These were (a) explanations in terms of equilibrium law and reaction quotient (“EL/RQ”), (b) explanations in terms of Le Châtelier’s principle (“LCP”), and (c) explanations in terms of reaction rates and collision theory (“RR/CT”). These codes were used during a second re-reading of the interview data. Table 3 shows the codebook for these codes. This coding was analyzed for the frequency and patterns of the types of explanations provided for the events discussed in the interviews, as well as patterns with respect to each teacher’s educational and certification backgrounds.

<table>
<thead>
<tr>
<th>Language Categories</th>
<th>Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>EL/RQ</td>
<td>Language in line with equilibrium law; “reaction quotient”, “Q”, “Q versus K”, etc.</td>
</tr>
<tr>
<td>LCP</td>
<td>Language in line with Le Châtelier’s principle; “shift”, “stress”, “use up”, “move away from”, “counteract”, etc.</td>
</tr>
<tr>
<td>RR/CT</td>
<td>Language in line with reaction rates and collision theory; “collide”, “orientation”, “activation energy”, etc.</td>
</tr>
</tbody>
</table>

Table 3. Codebook for analysis of interview data for the language used to describe chemical equilibrium.
**Coding for Teacher Practice of Integration of Equilibrium and Reaction Rates**

The third research question concerned the practice of teacher integration of the topics of chemical equilibrium and reaction rates in their classrooms, and their reasons for this practice. In order to answer this research question, a third re-reading of the transcripts was conducted, specifically looking for statements about classroom practice. Careful attention was paid to the last part of each interview, where teachers were asked outright to discuss the integration of the two topics. Along with identifying simple “Yes” or “No” responses, emergent codes were used during the analysis for each participant’s reasons, and evidence that their responses were indicative of what actually took place in their classrooms. In addition to looking for patterns in their responses, this information was compared to the data gleaned from the first two research questions to determine whether (a) the alternative conceptions held by the teachers affected whether or not they integrated the topics in their lessons, and (b) their decision to integrate the topics was related to their educational background and teaching degrees.

**Coding for Conceptual Change**

During a fourth re-reading, interview data were coded to note any change in reasoning as the interview progressed. This was an emerging theme that developed during the pilot studies, and since the literature suggests that probing responses and graphing can be powerful components of conceptual change, it was worth exploring. It became clear during the pilot studies that the participants were altering their responses to questions after being asked to explain their initial response, and again after being asked to graph their response. Thus, the interview guide was modified so that, during the interview, participants were asked to give a prediction of what would happen to the concentrations and rates of the reaction when each change was made to the system. They were then asked to explain their predictions, and then complete a graphing task while thinking aloud. This data also aligns with Research Question 2.

**Triangulation of Data**

Finally, the interviews were analyzed for whether or not the initial, explanation, and graphing responses given to an answer matched the information provided by the participant in the CECT assessment, in order to provide evidence of convergence validity for the study. When these three types of responses were different during the interview, the CECT response was compared to the initial response of the participant, since the CECT was administered before the interview, and the explanation and graphing responses could have been different due to a conceptual change effect.
Chapter 4

Results

4. Overview

This study aimed to identify the conceptions of experienced teachers of advanced high school chemistry about chemical equilibrium and rates of reactions, as well as the ability of teachers to describe the concepts of chemical equilibrium in terms of reaction rates. Also, it attempted to relate these alternative conceptions to teachers’ educational backgrounds, teaching certifications held, and classroom experience. The study explored conceptual change during the interview and task processes, as well as how well the Chemical Equilibrium Concepts Test (CECT) identified the alternative conceptions of these teachers. Lastly, the study investigated teacher ideas with respect to presenting these topics in the classroom, and if/how they were integrated. The interview focused around the reaction,

\[ 2\text{NO}(g) + \text{O}_2(g) \rightleftharpoons 2\text{NO}_2(g) + \text{heat} \]

and participants were asked about the reaction, the meaning of the double arrow, the meaning of the equilibrium expression, how the reaction could be pictorially represented, what observations would be expected upon mixing the reactants, the equilibrium state, and what would happen if certain changes were made to the system once equilibrium was established. The teachers were also asked to create graphs of changes to the concentrations of species and the rates of the forward and reverse reactions when changes to equilibrium were made.

The major findings are summarized below, and are described in detail in the following sections of this chapter:

1. Forty-seven alternative conceptions, expressed in almost 150 instances, were held by the teachers in this study. Though these alternative conceptions have been reported in the literature, this finding was unique in that it identified these alternative conceptions within a group of teachers with an average of 11.4 years’ experience teaching advanced high school chemistry. This demonstrates that the alternative conceptions commonly found in the literature, held by students and teachers with little or no teaching experience, remained throughout teachers’ careers. Alternative conceptions regarding reaction rates were the most common.

2. These experienced teachers generally had difficulty integrating the concepts of chemical equilibrium with reaction rates, expressing many of the alternative conceptions commonly found in the chemical education literature. Alternative conceptions regarding reaction rates were most common.
3. When the teachers in the study explained the various equilibrium and reaction rate concepts, they frequently could not successfully incorporate these ideas into the graphing tasks and demonstrated a shallower understanding about these concepts than was expected.

4. The alternative conceptions expressed, and the ability of teachers to integrate chemical equilibrium with reaction rates, was less related to the educational backgrounds of the participants, and more related to (a) the number of years teaching experience and (b) whether they had primary certifications in chemistry.

5. The language used to describe chemical equilibrium was divided between the use of Le Châtelier’s principle, Equilibrium Law and Reaction Quotient, and Collision Theory and Reaction Rates, based upon what was being described. Le Châtelier’s principle along with Equilibrium Law and Reaction Quotient language was most often used to describe changes in concentration, whereas Collision Theory language was used to describe changes in rates. Those teachers who scored better on the CECT and expressed fewer alternative conceptions generally used the language of Collision Theory more often.

6. The teachers self-reported, and the interview data suggests, that they generally did not integrate the concepts of chemical equilibrium and reaction rates in their classrooms.

7. The Chemical Equilibrium Concepts Test (CECT) was an effective indicator of the teachers’ understanding of these topics.

8. Conceptual change during the interviews and graphing tasks was a common occurrence, though there were instances of both positive and negative conceptual change.

The sections of this chapter are organized as follows: Section 4.1 describes the backgrounds of the teacher participants, while Section 4.2 details the conceptions and alternative conceptions the teachers maintained about chemical equilibrium and reaction rates and the results of the graphing tasks. Section 4.3 focuses on the relationship between educational and teaching background and conceptions of equilibrium and reaction rates. Section 4.4 explores the language used to describe equilibrium and reaction rates. Section 4.5 outlines the self-reported integration of the topics and how it compares with interview data. Section 4.6 reports on the similarity between interview and assessment data. Finally, Section 4.7 shows instances of conceptual change during the course of the interviews.

4.1. Teacher Participants

Thirteen public high school teachers with at least five years’ experience teaching advanced-level chemistry participated in the study. Table 4 lists the degrees and certifications held by each of the teachers. The group consisted of six women (46%) and seven men (54%) and had an average of 11.4 years of experience teaching advanced chemistry. All held permanent or professional certification in chemistry and were tenured in their school district. Ten of the
teachers held primary certification in chemistry, while three held primary certification in biology. All but one of the participants taught Advanced Placement Chemistry in their schools; the remaining participant (D) taught the Higher-Level Chemistry IB (International Baccalaureate) Curriculum. Participant K was part of the New York State Master Teacher Program. Seven (54%) of the participants taught in Nassau County schools (A, B, C, D, E, J, and K); while six (46%) taught in Suffolk County schools (F, G, H, I, L, and M). Five of the teachers (38%; G, H, K, L, and M) reported having taken a professional development course that included, in part, information about chemical equilibrium. Eight (62%) of the teachers had undergraduate degrees in chemistry (with one (K) holding a degree in chemistry education), and seven (54%) had worked in industry or other labs before becoming teachers. Only three of the participants (23%; C, F, and I) reported that they had not taken a course in physical chemistry in college at any point. A course in thermodynamics would indicate exposure to a more thorough treatment of equilibrium and reaction rates. Five of the teachers (38%; A, E, H, J, and K) held only one teaching certification, which is uncommon for teachers on Long Island.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Gender</th>
<th>B.S.</th>
<th>M.S. (*Ph.D.)</th>
<th>NYS Certification(s)a</th>
<th>Advanced Experienceb</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Chemistry Secondary Ed.</td>
<td>Chem 7-12 Perm</td>
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</tr>
<tr>
<td>B</td>
<td>F</td>
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</tr>
<tr>
<td>C</td>
<td>M</td>
<td>Biology</td>
<td>Biology</td>
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<tr>
<td>D</td>
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<td>Chem 7-12 Perm</td>
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<tr>
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<tr>
<td>K</td>
<td>M</td>
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</tr>
<tr>
<td>L</td>
<td>F</td>
<td>Chemistry</td>
<td>Chemistry</td>
<td>Chem/GS 7-12 Perm Phys 7-12 Perm Math 7-12 Perm</td>
<td>12</td>
</tr>
<tr>
<td>M</td>
<td>F</td>
<td>Chemistry, Biology</td>
<td>Neuroscience*</td>
<td>Chem 7-12 Perm Bio/GS 7-12 Perm</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 4. Demographic data for study participants. M=male; F=female; Perm=Permanent NYS Certification; Prof=Professional NYS Certification. *Primary Certifications and listed first. "Years of experience teaching advanced-level (AP/IB) chemistry.
Additional Participant Profiles

Presented in this section is additional information about each of the teacher participants. It includes what classes the teachers taught. Although this study focused on teachers who taught advanced level chemistry (AP or IB), most of the participants also taught lower level classes in chemistry, including Regents Chemistry. Regents chemistry, officially called “Physical Setting – Chemistry,” is the statewide introductory chemistry course, and includes only introductory concepts in chemical equilibrium and reaction rates (New York State Department of Education, 2019c). The descriptions also include the names of the textbooks used by the participants, since details of how textbooks treat equilibrium and reaction rates are provided in Section 3.2. Information about whether or not each participant took courses in thermodynamics (which would indicate a more thorough background in the topics of equilibrium and reaction rates) and professional development courses pertaining to equilibrium is also provided. Finally, their scores on the CECT are provided.

Teacher A

Before completing her master’s degree, Teacher A worked for several years in labs in a university setting. She typically taught Advanced Placement (AP) Chemistry, Honors Chemistry, and Science Research. She reported the use of Chemistry: Matter and its Changes, by Brady et al. as her primary AP text, but used others for questions. She has had courses in physical chemistry but had not had any professional development courses specifically or in part regarding chemical equilibrium. On the CECT, she correctly answered 43 of 47 questions.

Teacher B

After receiving her doctorate, Teacher B worked at a genetic engineering company for several years, before doing some adjunct teaching in college. From there, she worked as a teaching assistant at the high school where she worked at the time of this study, and ultimately decided to obtain certification and begin a secondary school teaching career. She taught Advanced Placement (AP) Chemistry and Science Research. She reported the use of Chemistry, by Zumdahl et al., as her primary AP text, but used books by Chang and McMurray for reference. She has had courses in physical chemistry but had not had any professional development courses specifically or in part regarding chemical equilibrium. On the CECT, she responded correctly to all 47 questions.

Teacher C

Teacher C’s education specialized in genetics and genetic engineering. After spending five years working in genetic research labs, he decided to change careers and enter the teaching profession. He taught primarily Biology classes until 6 years prior to this study, when he began to teach chemistry. At the time of this study, he taught Advanced Placement Chemistry, Regents Chemistry (the statewide introductory chemistry course), and Regents Living Environment, and reported the use of Chemistry, by Brown and Lemay as his AP Chemistry text. He had not taken a course in physical chemistry or had any professional development courses specifically or in part regarding chemical equilibrium. On the CECT, he responded correctly to 19 of the 47 questions.
Teacher D
After working in research for a short time, Teacher D decided to enter the teaching profession with the intention of teaching high school biology. He had taught Biology and Chemistry classes, but admitted that he did not enjoy teaching biology as much as he enjoyed teaching chemistry. At the time of this study, he taught Regents and Honors Chemistry, and the Higher-Level International Baccalaureate (IB) Chemistry course. He reported the use of Chemistry: The Central Science, by Brown, et al., as well as Cambridge’s IB Chemistry, by Owens as his IB Chemistry texts. He reported that he took courses in physical chemistry but had not taken any professional development courses specifically or in part regarding chemical equilibrium. On the CECT, he responded correctly to 45 of 47 questions.

Teacher E
At the time of this study, Teacher E reported that he was the first to teach the Advanced Placement (AP) Chemistry course at his school, and taught Honors Chemistry and other science electives as well. He had been an AP grader, and used Chemistry, by Zumdahl as his primary AP text. He has had courses in physical chemistry but has not had any professional development courses specifically or in part regarding chemical equilibrium. On the CECT, he correctly answered 41 of 47 questions.

Teacher F
Teacher F worked in the clinical lab science field for a few years until entering and obtaining his doctorate degree from Chiropractic School. He worked as a chiropractor and a lab technician, until friends and family members convinced him that he would enjoy teaching, prompting him to obtain teaching certifications. At the time of the study, he had taught Advanced Placement Chemistry, Honors Chemistry, and Regents Chemistry. He reported the use of Chemistry: The Central Science, by Brown, et al. as his primary text for AP Chemistry. He had not taken courses in physical chemistry, nor had he taken any professional development courses specifically or in part regarding chemical equilibrium. On the CECT, he responded correctly to 37 of 47 questions.

Teacher G
Although Teacher G obtained his certification to teach chemistry while working on his bachelor’s degree, he did not pursue teaching until after he earned his master’s degree and worked as a chemist for a short time. In addition to teaching AP Chemistry, he also taught Honors Chemistry, and reported using Zumdahl’s Chemistry as his AP Chemistry textbook. He had taken a course in thermodynamics. He had also taken a professional development course, sponsored by the College Board, which focused in part on chemical equilibrium. On the CECT, he responded correctly to 39 of 47 questions.

Teacher H
Teacher H taught Regents Chemistry as well as AP Chemistry at her school. At the time of the study, her students took AP Chemistry as their first course in chemistry and were often 10th graders. She used Brown, et al.’s Chemistry: The Central Science as her AP text. She had taken courses in thermodynamics as well as a College Board-sponsored course that focused, in part, on chemical equilibrium. On the CECT, she responded correctly to 41 of 47 questions.
Teacher I
Teacher I began teaching chemistry in 2001, after many years of teaching biology, and had taught AP Chemistry since 2008, in addition to Honors Chemistry. He reported using *Chemistry*, by Zumdahl as his primary AP text. He had not had courses in physical chemistry, nor had he taken any professional development courses specifically or in part regarding chemical equilibrium. On the CECT, he correctly answered 43 of 47 questions.

Teacher J
Teacher J typically taught Advanced Placement (AP) Chemistry, Honors Chemistry, and Regents Chemistry at her school, and reported the use of *Chemistry*, by Zumdahl as her primary AP text. She did take courses in physical chemistry but had not had any professional development courses specifically or in part regarding chemical equilibrium. On the CECT, she correctly answered 42 of 47 questions.

Teacher K
In addition to AP Chemistry, Teacher K also taught Advanced and Regents Chemistry, and was proud to have been selected into the New York State Master Teacher Program. He reported using Zumdahl’s *Chemistry* as his primary AP text. He had taken courses in physical chemistry, and had also taken a professional development course, sponsored by the College Board, that addressed chemical equilibrium as part of the course. On the CECT, he correctly answered 39 of 47 questions.

Teacher L
Teacher L reported that she always knew that she wanted to teach. After earning her master’s degree, she first taught at the high school, and then moved to college teaching for many years before returning to high school. In addition to teaching AP Chemistry, she also taught Regents Physics and an Applied Chemistry elective. She used the AP edition of Chang’s textbook for the AP course. She had taken a course in thermodynamics, as well as a professional development course that focused, in part, on chemical equilibrium. On the CECT, she responded correctly to 39 of 47 questions.

Teacher M
After earning her Ph.D., Teacher M completed two post-doctoral assignments at different universities, where she worked with students involved in research projects for the Intel Science Research Competition. During that time, she found that she enjoyed interacting with those students, and so, while working as a researcher, she completed the educational requirements for teaching certification. During her time at the high school she taught at, she began the science research program, taught Regents and non-Regents Biology and Chemistry, and developed science electives. At the time of the study, she taught AP Chemistry and Science Research. She reported using Zumdahl’s *Chemistry* as her AP text. She had taken courses in thermodynamics as well as a professional development course that focused, in part, on chemical equilibrium. On the CECT, she responded correctly to 39 of 47 questions.
4.2. Teachers’ Conceptions of Equilibrium and Reaction Rates

The first two research questions in this study were concerned with the conceptions of the teachers with respect to chemical equilibrium and reaction rates, and how teachers used the concepts of reaction rates to describe changes to a system at equilibrium. The thirteen teachers varied in the conceptions they maintained, though there were quite a few alternative conceptions that were common to several teachers. A total of forty-seven alternative conceptions were expressed by the participants during the course of the interviews, many of which had been identified previously in the literature. Table 5 lists the number of alternative conceptions uncovered during this study by concept area, as well as the percentage of teachers expressing alternative conceptions in these areas (see below for examples). A complete list of alternative conceptions identified in this study can be found in Appendix P. Since these were experienced teachers, and most previous studies have focused on pre-service or inexperienced teachers, these results demonstrate that alternative conceptions did not completely resolve themselves with experience.

<table>
<thead>
<tr>
<th>Topic Area</th>
<th>number alternative conceptions identified</th>
<th>number (%) of teachers expressing alternative conceptions in this area</th>
</tr>
</thead>
<tbody>
<tr>
<td>meaning of the equilibrium constant, K</td>
<td>4</td>
<td>3 (23.1)</td>
</tr>
<tr>
<td>the equilibrium condition</td>
<td>3</td>
<td>9 (69.2)</td>
</tr>
<tr>
<td>the approach to equilibrium</td>
<td>4</td>
<td>5 (38.5)</td>
</tr>
<tr>
<td>a change to the equilibrium condition,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>upon the addition of reactant</td>
<td>10</td>
<td>11 (84.6)</td>
</tr>
<tr>
<td>upon an increase in temperature</td>
<td>6</td>
<td>11 (84.6)</td>
</tr>
<tr>
<td>upon a decrease in volume</td>
<td>11</td>
<td>12 (92.3)</td>
</tr>
<tr>
<td>the role of a catalyst</td>
<td>3</td>
<td>9 (69.2)</td>
</tr>
<tr>
<td>other alternative conceptions identified</td>
<td>6</td>
<td>10 (76.9)</td>
</tr>
</tbody>
</table>

Table 5. Alternative conceptions identified in this study by topic area.

Discussed in the following sections are detailed summaries of the conceptions of these teachers on the various topics covered during the interviews, and the most pertinent alternative conceptions identified. Where responses were coded, a method previously described in the literature was used (see Table 2, modified from Ozden, 2009).

Overall Conceptions Regarding the Reaction Presented

At the beginning of the interview, teachers were shown the exothermic equilibrium reaction between NO and O₂, shown above. Without asking a specific question, they were prompted to provide their initial thoughts about the equation. Table 6 shows the initial ideas that the participants provided about the equation. The most common initial ideas about the reaction were that it was an exothermic reaction and that it was an equilibrium reaction. These two ideas were given by all participants as either their first or second response after being asked to describe the reaction. Ten of the 13 participants mentioned that the reaction was exothermic, but only seven mentioned that it was an equilibrium reaction without being specifically asked about it. This may be because the participants assumed that it was at equilibrium because they knew ahead of time...
that this study was about equilibrium and felt that they did not need to mention that. Other common initial ideas about the reaction were that all of the species were gases, that there were more moles of gas on the reactant side of the equation, and how that would affect the reaction with respect to a pressure change. None of the teachers noted that the NO₂ would itself dimerize in another equilibrium reaction \(2\text{NO}_2 \rightleftharpoons \text{N}_2\text{O}_4\), though this dimerization reaction is a key example of equilibrium reactions given in each of the texts used by the participants.

<table>
<thead>
<tr>
<th>Reaction description</th>
<th>1st response</th>
<th>2nd response</th>
<th>3rd response</th>
<th>Other responses</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction is exothermic</td>
<td>H,K,M</td>
<td>A,F,I,L</td>
<td>E</td>
<td>C,J</td>
<td>10</td>
</tr>
<tr>
<td>All species are gases</td>
<td>F,G,L</td>
<td>J</td>
<td>E</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>“More” moles of gas on reactant side, but no direct mention of LCP</td>
<td>H</td>
<td>J,M</td>
<td>L</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Mention of LCP with respect to pressure</td>
<td>K</td>
<td>A,F</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Rates are equal</td>
<td>D</td>
<td>C</td>
<td>E</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Synthesis reaction</td>
<td>C</td>
<td>K</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Concentrations are constant</td>
<td></td>
<td></td>
<td>C</td>
<td>E</td>
<td>2</td>
</tr>
<tr>
<td>Mention of LCP with respect to temperature</td>
<td>M</td>
<td>C</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Nitrogen monoxide reacts with oxygen to give nitrogen dioxide</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Oxidation reaction</td>
<td>E</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Mention of ∆H, but not exothermic</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Decreasing entropy</td>
<td>L</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Mention of LCP</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Mention of stoichiometry</td>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Mention of thermodynamics</td>
<td>L</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Mention of rates</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Reference to equilibrium question</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6. Initial descriptions of the reaction \(2\text{NO}(g) + \text{O}_2(g) \rightleftharpoons 2\text{NO}_2(g) + \text{heat}\). P=response after interviewer prompt; LCP=Le Châtelier’s principle.

When asked about the meaning of the double arrow in the chemical equation, the initial responses were, in general, split among describing it as an indication that the rates of the forward and reverse reactions are equal (C, G, J), an indication that the reaction was reversible (A, B, E, M), or simply an indication of the reaction being an equilibrium reaction (F, I, K, L). Participant H described the double arrow initially as an indication that the concentrations of the species were constant. An alternative conception was identified in the initial description of the double arrow provided by teacher B, who said that the rates of the forward and reverse reactions were equal.
only because the arrows were of equal length. When discussing the meaning of the double arrow in more detail, three teachers (B, E, F) spoke about the double arrow as an indication of the dynamic nature of equilibrium. Upon further probing, however, the common alternative conception that the reaction oscillates back and forth was indicated by four teachers (D, E, F, and G):

G: …My impressions of equilibrium was that it was always...there’s always this back and forth going on...you know, it’s when we say that the forward rate increases and the reverse rate slows down, it’s not a steady thing. There’s always, you know, it’s kind of fluctuating back and forth until it reaches the equilibrium point…

D: …So even though it's at equilibrium to the eye, on the macroscopic scale, it looks like the reaction stopped, on the atomic scale, you can clearly see that the reaction's going back and forth

F described the use of a see-saw analogy to describe equilibrium to his students, which solidified the conception that the reactions take place one at a time:

F: As soon as I think equilibrium, my initial thought is that the reaction is at equilibrium, which means my concentrations are constant, the rates of the forward and reverse reaction are going back and forth…I'll teach it, a lot of times, like a seesaw. So, um, I actually visualize the seesaw going back and forth, where you have a dynamic process going on…

Conceptions about Equilibrium at the Sub-microscopic Level

Teachers were asked to draw a representation of this reaction just as two moles of NO and one mole of O₂ were added to a container, and before any reaction had a chance to occur. The teachers were free to represent the reactants in any way they chose. Eight of the 13 participants (62%) chose to draw particle diagrams, a concept that has become increasingly stressed on the AP and Regents Chemistry exams. In order for the task to be coded as SU (sound understanding) the diagram had to (a) show nitrogen and oxygen atoms differently and in correct molecular forms, (b) indicate in some way that the particles were gases and thus filled the container in a randomized way, (c) indicate the stoichiometry of the reaction, and (d) include several molecules of each type. A PU (partial understanding) coding was applied to diagrams that did not include all these features. Drawing only two molecules of NO and one molecule of O₂ represented a mole concept alternative conception that there is no difference between moles and molecules. This common alternative conception was demonstrated by teachers C, G, J, K, L, and M, or 46% of the teachers in the study. Examples of SU-coded and AC-coded diagrams are shown in Figure 3 and Figure 4, respectively, and Table 7 shows the characteristics and coding of all the participants’ diagrams.
Teachers were then asked to draw a representation of this reaction after the reaction had a chance to occur and had reached equilibrium. Again, diagrams were coded based upon their features. For an SU coding, diagrams had to (a) show all three species as gases, including randomization of reactants and products, (b) take into account the equilibrium constant, and (c) indicate the stoichiometry of the reaction. A PU (partial understanding) coding was applied to diagrams that did not include all these features. A prevalent alternative conception in this group of teachers was drawing an equal number of NO and NO₂ molecules at equilibrium. This alternative conception, that there is a simple mathematical relationship between reactants and products at equilibrium based on reaction stoichiometry, is commonly found in the literature, and was held by 38% of the teachers (C, F, K, L, and M). Another alternative conception that three teachers (C, J, and M) held was that the same number of NO and O₂ molecules would exist...
before and after equilibrium. However, later in the interview, when the idea of concentrations at equilibrium was probed again, theses teachers did not repeat that alternative conception. It may be, that for these diagrams, these teachers were simply thinking in a more abstract way. One alternative conception held by teacher L was that, since the equilibrium constant was large, one of the reactants would be completely consumed in the reaction. In her pre-equilibrium diagram, she put only 2 molecules of NO and one of O₂. Then, when she drew the equilibrium diagram, she initially had only NO₂ and none of the reactants. When asked why she drew only NO₂:

L: …So if it's[the equilibrium constant] large, then you're definitely going to have a lot more product than reactants, so if I just put in one little…O₂ molecule, at least there would be something left…And then it wouldn't be able to react, so it would have to stay there. So then I would have more product, and this [NO] would be gone.

SG: Okay. So at equilibrium, you have NO₂, you have O, but you have no NO?

L: …Right. So that would have been like the limiting reagent…

Once again, this alternative conception was not repeated later in the interview and may be the result of misunderstanding the question. Interview time did not permit the re-exploration of her diagram later in the interview. Table 8 shows the characteristics and coding of all the participants’ diagrams, and examples of SU-coded and AC-coded diagrams are shown in Figure 5 and Figure 6, respectively.

<table>
<thead>
<tr>
<th>NO₂, NO and O₂ drawn</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>asked about K, or mentioned an assumed K</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>more NO₂ than NO/O₂, or based on assumption</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>ratio of NO:O₂ still 2:1</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
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<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>reaction stoichiometry (decrease NO, decrease O₂ by 1/2)</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
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<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>ratio of NO₂/NO/O₂</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
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<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>all mixed/indicated that all mixed</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
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<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>at equilibrium, stoichiometric ratio of reactants/products (AC)</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>same number of NO, O₂ as before (AC)</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>used up a reactant (AC)</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
</tbody>
</table>

**Table 8. Coding of diagrams of species after equilibrium is established.** SU=sound understanding; PU=partial understanding; PU-AC=partial understanding with a specific alternative conception mentioned; AC=alternative conception; NU=no understanding. (*diagram edited later in interview)
Conceptions Regarding the Equilibrium Constant and its Meaning

The equilibrium expression for this reaction can be expressed as a $K_c$ using concentrations, or as a $K_p$ using partial pressures, since the system is gaseous (Figure 7).

$$K_c = \frac{[\text{NO}_2]^2}{[\text{NO}]^2[\text{O}_2]} \quad \text{or} \quad K_p = \frac{(p_{\text{NO}_2})^2}{(p_{\text{NO}})^2(p_{\text{O}_2})}$$

Figure 7. The $K_c$ and $K_p$ expressions for the system in this study.

All thirteen teachers in the study were able to write the equilibrium expression for the reaction when asked to do so. All but two teachers wrote the equilibrium expression as a $K_c$. Teachers L and M wrote both the $K_c$ and $K_p$ expressions. No teacher wrote only the $K_p$. When asked about the meaning of the equilibrium expression and constant, there were four basic types of responses. Teachers D, F, and I described the equilibrium expression as purely a mathematical entity, resulting in the same value of the equilibrium constant each time different concentrations are used:

**D:** …at equilibrium, the concentration of the product squared divided by the concentration of the first reactant squared times the oxygen to the first.

**F:** The equilibrium constant is calculated based on concentration of your products over the concentration of the reactants…I really don't think about writing it…It's just products over reactants and that's your law of mass action.

**I:** …if you were to take the concentrations, at equilibrium, of the nitrogen dioxide and square it, divided by nitrogen monoxide squared and oxygen, you would get some value that doesn't change as long as you don't change the temperature.

These teachers, who defined the expression quite literally, were those with undergraduate degrees outside of chemistry. Teacher C also had a degree outside of chemistry, and described the equilibrium constant incorrectly, with some confusion:
C: Well, it's the equilibrium constant. So basically the rates would be equal. So if you're getting three moles of reactants becoming two moles of products, that would be this Keq value that would tell you that you're- the rates are equal. With the concentrations being constant. You begin with Keq.

Those teachers with undergraduate degrees in chemistry (A, B, E, G, H, J, K, L) were more general, describing the equilibrium expression as (a) a measure of a ratio of products and reactants at equilibrium, or (b) a measure of which species were present in higher amounts at equilibrium:

J: ...it's going to be a value that helps me know how much product we're producing in this equilibrium.

K: The equilibrium is dependent on all those concentrations...And to me, it's a ratio of the products at equilibrium and the reactants at equilibrium.

L: It's a ratio proportion, of the amount of product that you have compared to the amount of reactant that you have. Or the pressure of the product over the pressure of the reactant once equilibrium is established.

G: For me, it represents where you are, where your current equilibrium is. Whether you're in more of a reactant-favored equilibrium, or in a more product-favored equilibrium.

One last way in which the equilibrium constant and expression were defined was as an indication of how the problem is going to proceed:

M: Well, this is...my jumping off point for the next part of my AP question, which is probably going to be to make a prediction. Maybe do a Q problem. Am I at equilibrium? Which way am I going to shift next? So... I'm going to look in the problem for partial pressures or moles, and the volume of the container, to go ahead with it.

When the teachers were asked what a large value for the equilibrium constant meant to them, all but one teacher responded by expressing that more products would be present at equilibrium. A typical response is shown by teacher F:

F: That would tell me that the equilibrium favors the products. The system sits more towards the product side of the reaction.

However, teacher M suggested that a large value for K would mean that the reaction,

M: ...will proceed in the forward direction at equilibrium.

This idea represents an alternative conception, since the rates of the forward and reverse reactions would be equal at equilibrium, and a shift in one direction would not occur at
equilibrium. Two other alternative conceptions regarding the equilibrium constant were identified and will be discussed in the later parts of this chapter, since they are related to the consequences of a disturbance to a system at equilibrium.

**Conceptions Regarding the Approach to Equilibrium**

After the discussion about the equilibrium constant and its meaning, teachers were provided with a scenario in which two moles of NO and one mole of O₂ were added to a one-liter container, the container was sealed, and the reactants were allowed to react. From this point, they were asked about what would happen to the reaction as it approached equilibrium in terms of the macroscopic properties, concentrations and rates of the forward and reverse reactions.

**Mixing of Reactants – macroscopic description**

The teachers were first asked two questions about the approach to equilibrium on a macroscopic scale: (a) What would be noticed as the reaction proceeded toward equilibrium? (b) How would an observer know that equilibrium had been achieved? The expected answer was the development of a brown color, the intensity of which remains constant once the reaction has reached equilibrium. Three teachers (A, E, and J) gave this answer as their initial response:

**A**: NO₂ is brown…oxygen is colorless. NO is probably colorless…you would see a slow appearance of brown color, and it would intensify until a certain point where it wouldn't get any darker.

**E**: It's going to transition into nitrogen dioxide. This [NO] is going to be clear, and that's [NO₂] going to be a brown gas. So it's going to transition from clear to a slight color change.

**J**: There would be a change in color, and eventually the color would remain constant.

There were four other types of initial responses. Teachers F, K, and L first discussed changes in concentration, without discussing how that might be measured:

**F**: If we were to draw a curve, you're going to start with your two-to-one ratio, and your concentration of the reactants is going to go down as you're producing a product…until you reach your equilibrium status…But at a certain point, you plateau it out, and we plateau out our product.

**K**: ...their amounts would decrease. Their concentrations would decrease, though not to the point where they're completely absent. You would still have some of them as well as the NO₂ gas.

**L**: I would expect to notice that the concentration of the NO and the O₂ decrease, and that there would be some NO₂ there…

Teacher I used a change in rates to observe the attainment of equilibrium, also without specifically identifying how this could be measured:
I: You would make some product, and...when equilibrium is reached, you would have the reactants going to products, products going to reactants at the same rate.

Teacher B suggested utilizing both a change in concentration and rate to determine the equilibrium point:

B: So, basically you would say that the NO concentration decreases, the O₂ concentration decreases. They decrease at different rates...They would at some point plateau. At the same time the NO₂ is increasing, and you reach a point where the rate of forward reaction equals the rate of the reverse reaction, and the concentrations are constant.

A third category of initial responses was the discussion of a change to the number of moles or the amount of each species, rather than a concentration change. This was the initial response given by teachers D, G, and M:

D: I would notice that...the amount of NO, and the number of moles of O would go down.

G: So soon you’re going to see amounts of NO and O₂ go down over time as the amount of NO₂ increases over time.

M: In the beginning, you'll have...none of it [NO₂], and then gradually it will come up and then level off... [NO and O₂] are in a two-to-one ratio. So, this will be used up at twice the rate of that. That's going to have a steeper slope down. The other guy will slope down, and they'll all level off...if you graphed them...you just look for that first instant where each line...leveled off to where they're parallel. As soon as they're all parallel, constant not changing.

A fourth type of initial response included macroscopic changes other than a color change. C suggested that a temperature change would be observed, since the reaction is exothermic:

C: I would expect the container to get warmer.

An alternative conception was identified in the initial response of teacher H, who suggested that the forward reaction would occur to the point of equilibrium, and then stop:

H: If you put NO and O₂ in a reaction container, they would react to produce NO₂, so the forward reaction would go for a little while, until it reaches the value of K. And then there will be no noticeable change after that time.

When teachers were pressed about how they would actually measure these changes to rates and concentrations, in a lab setting, to know when they remained constant, they either admitted that they did not know how this was done, or suggested that they assumed there was a way of knowing this:
B: I would graph NO or O2 or NO2, and I would see that the concentration...if I had a means to measure them, which we pretend we do, I would see that the concentration stops changing at some point.

L: You would have to have some means of monitoring the amounts over time, and once the amounts seemed to remain constant, then I would say you've a pretty good indication that you've got to equilibrium.

F: In the lab setting? I couldn't tell you. I'll be honest...I've never had that discussion or never considered that. How would you know at the laboratory level. I only know from a theoretical level, on paper.

G: Obviously, it will be difficult to see it, but...they’ll eventually reach a balance point or an equilibrium point.

I: Well, once it's on a piece of paper and the double arrows are there, I assume equil[ibrum]- Um, I don't know. That's a good question. Never thought of it. Never thought about it.

An alternative conception was identified in the response from Teacher C, who said that equilibrium would be reached when you had 2 moles of NO and NO2 and one mole of O2:

C: I'm assuming you have the ability to calculate or figure out the number of moles. So, when you know that you had two moles of NO, one mole of O2, and two moles of the NO2.

When pressed further about how they would be able to tell that equilibrium had been reached in a lab, teachers D, F, I, K, L and M suggested that there was a possible color change.

**Predictions, Explanations and Graphing Tasks**

After the teachers discussed the macroscopic characteristics of equilibrium and the approach to it, the next line of questioning focused on what would happen to the concentrations of all species and the rates of the forward and reverse reactions as reactants were mixed, after equilibrium was disturbed, when a catalyst was added, and when water was added. In addition to being asked to predict, and then explain, what would happen over time, the teachers were asked to graph each event. The graphs provided insight into how each teacher conceptualized each event and were valuable in helping to identify the alternative conceptions of these teachers, for answering Research Question 1. The next sections describe the prediction/explanation responses of the participants, analyzes their graphs, and identifies the alternative conceptions held by these teachers.

**Mixing of Reactants – changes in concentration**

The teachers were first asked to predict, explain, and then graph what would happen to the concentrations of each of the three species from the time the NO and O2 were added to the one-liter container, until the time that equilibrium was established. The expected prediction was that...
the concentrations of the NO and O₂ would decrease, and the concentration of the NO₂ would increase until equilibrium was established, at which time the concentrations of each of the species would remain constant. For the explanation as to why this would occur, the simplest expected response was that as the reaction occurred, the NO and the O₂ are consumed as NO₂ is produced, until the concentrations of all species level off due to the simultaneous concurrence of both the forward and reverse reactions. When graphing the approach to equilibrium, it was expected that the change in concentrations and eventual consistency were shown, the large value of the equilibrium constant was reflected in the graph, the stoichiometry of the reaction was considered, and no simple, arithmetic relationship between reactants and products are indicated or shown. These were the criteria for a response obtaining an SU (sound understanding) coding. A PU (partial understanding) coding was applied to responses and graphs that did not include all these criteria. For all concentration graphs, the x-axis is concentration, and the y-axis is time (see Appendix H for the coding assigned to each teacher’s predictions, explanations and graphs).

All 13 teachers correctly predicted what would happen to the concentrations of the species as the reaction approached and established equilibrium. Complete explanations were provided by only two teachers (A, J; 15%). Incomplete explanations were provided by 10 teachers (B, C, D, F, G, H, I, K, L, and M), who did not discuss what would happen at equilibrium in terms of concentrations. Teacher E offered only that the concentrations must change as they did to establish equilibrium. Of these teachers, five drew graphs that met all the criteria for SU coding (B, D, E, H, and J), which included what would happen at equilibrium. In fact, all the teachers’ graphs leveled off at equilibrium. An example of an SU-coded graph is shown in Figure 8. Two teachers (A, and I) received a PU coding for their graphs, because they did not show an immediate decrease in the concentration of the reactants. Figure 9 shows an example of this graph. Three teachers (G, K, and M) received a PU coding for their graphs for not taking the large equilibrium constant into account. Figure 10 shows an example of this error. Teacher L received and PU-AC coding, because she indicated that she had never seen the lines cross, and thus did not draw it that way, her statement representing an alternative conception.

Figure 8. SU-coded concentration graph for the mixing of NO and O₂ [Teacher D]

Figure 9. PU-coded concentration graph for the mixing of NO and O₂ [Teacher I]
Two alternative conceptions were identified in an exchange with teacher C. First, that equilibrium would be reached when two moles of NO₂ were formed, and second, that the reverse reaction begins after the forward reaction occurs:

C: …as we approach equilibrium…This [NO₂] would go up and these two [NO and O₂] would go down…And then when you reach two moles of NO₂, again, these would become more constant. You’d get two and the one, and you’d be in equilibrium.

SG: Okay. So when does this- So, as this reaction goes…NO plus O₂, they react, they react to form the NO₂. When does the NO₂ start to decompose to give you the other two?

C: When you reach the two moles of the NO₂.

His graph, shown in Figure 11 reflects the first of those alternative conceptions:

Not only did teacher F not take the large equilibrium constant into account, he demonstrated the alternative conception that at equilibrium, the concentrations of NO and NO₂ were equal. Figure 12 shows the concentration graph that F drew, demonstrating this alternative conception.
According to him, his difficulty in determining where the concentrations would be at equilibrium was based on the stoichiometry of the reaction, as he reported that he had not worked with an equation before that had the same coefficients for different substances:

**F**: …I always work with the Haber process when I’m teaching this and believe it or not…I've never done an equilibrium equation in class where I had equal number of moles. So … I have to admit that you kinda got me on that one…But now…this is how I would respond, because I've had some time to think about it, because that was really bugging me…

Thus, nearly a quarter of the graphs (23%) contained alternative conceptions.

**Mixing of Reactants – changes in rate**

After discussing the changes to concentration on the approach to equilibrium, teachers were asked to predict, explain, and then graph what would happen to the rates of the forward and reverse reactions from the time the NO and O\textsubscript{2} were added to the one-liter container, until the time that equilibrium was established. The expected prediction was that the rate of the forward reaction would decrease, and the rate of the reverse reaction would increase from zero until equilibrium was established, at which time the rates of both reactions would be equal and constant. For the explanation as to why this would occur, the simplest expected response was that as the forward reaction occurred, the NO and the O\textsubscript{2} are consumed and less collisions between them would take place resulting in a lower rate. Conversely, as the product is produced, there is a greater likelihood of collisions between NO\textsubscript{2} molecules, resulting in a higher rate of reaction. At equilibrium, just as reactants are colliding to form products, products are colliding to form reactant, resulting in a constant and equal rate for the forward and reverse reactions. When graphing the approach to equilibrium, it was expected the rate of the forward reaction would be decreasing, and the rate of the reverse reaction would be increasing from zero. These were the criteria for a response obtaining an SU (sound understanding) coding. A PU (partial understanding) coding was applied to responses and graphs that did not include all these criteria. For all rate graphs, the x-axis is rate, and the y-axis is time (see Appendix I for the coding assigned to each teacher’s predictions, explanations and graphs).
Ten of the thirteen teachers understood that as the reaction approached equilibrium from the mixing of the reactants, the rate of the forward reaction would decrease, and the rate of the reverse reaction would increase, due to the relative amounts of collisions between reactants and products. These teachers were also able to represent this concept on a graph. An example of a typical rate graph for the mixing of reactants is shown in Figure 13.

![Figure 13. SU-coded rate graph for the mixing of NO and O₂. [Teacher H]](image)

The common alternative conception that the rate of the forward reaction increases as the reaction gets going was expressed by teachers C, K, and M:

**SG:** …what will happen to the rate of the forward? What will happen to the rate of the reverse?

**C:** Initially? The rate of the forward is going to increase because initially, that's all there is, is the forward reaction. And then when you approach two moles of NO₂, then the forward reaction \([C \text{ means reverse reaction, as indicated with movement of pencil on equation}]\) will start occurring.

**K:** The rate of the forward reaction is going to increase initially, because that's all you have. You only have reactants so…there's no way to get a reverse reaction if there's no products. So that's going to increase...

**M:** So initially, since you have no product, there's a very fast spike in the rate of the forward reaction, because you're all in production.

Other alternative conceptions were uncovered as well. After some time wrestling with drawing a graph consistent with the idea that both the forward and reverse rates had to increase, C decided that the only way to make the rates equal at equilibrium was to make them the same from the time the reactants are mixed to the time equilibrium is established. Figure 14 shows his graph. K also tried to show both rates increasing and, in addition, held the common alternative conception that the reverse reaction would not begin until sometime after the forward reaction occurred:
K: …and then, eventually, once…the reaction quotient exceeds the equilibrium ratio, it's [the reverse reaction] going to kind of kick back and start ramping up the reverse reaction, until they ultimately get to be equal.

and

K: And as I'm thinking...the reverse reaction wouldn't- you wouldn't have that at time zero. You'd have it at further out. And that's at…time- whatever. So that's why I'm starting at, not at the y-axis, but further over.

Figure 14. AC-coded rate graph for the mixing of NO and O₂. [Teacher C]

Figure 15 shows K’s graph, consistent with her alternative conceptions. Last, M maintained that the rate of the reverse reaction decreased from the time of mixing, as shown in Figure 16. Overall, 23% of the graphs contained alternative conceptions.

Figure 15. AC-coded rate graph for the mixing of NO and O₂. [Teacher K]

Figure 16. AC-coded rate graph for the mixing of NO and O₂. [Teacher M]

Conceptions Regarding Changing Equilibrium Conditions

By far, the most alternative conceptions held by these teachers related to what happens to the concentrations of reactants and products, and what happens to the forward and reverse reaction rates after the system is disturbed from equilibrium. The thirteen teachers knew well what changes could be made to the system in order to affect an equilibrium system. However, when
asked to explain or to draw a graph expressing how these changes affected the concentrations and rates of reaction, alternative conceptions were exposed. This section describes the conceptions of teachers regarding changing the equilibrium system by adding NO, increasing the temperature, and decreasing the volume.

**Addition of Reactant – changes in concentration**

Teachers were asked to predict, explain, and then graph what would happen to the concentrations of each of the three species when the equilibrium system was disturbed by the addition of more NO, and was allowed to re-establish equilibrium. The expected prediction was that the concentrations of the NO and O\textsubscript{2} would decrease, and the concentration of the NO\textsubscript{2} would increase until equilibrium was re-established, at which time the concentrations of each of the species would remain constant. For the explanation as to why this would occur, the simplest expected response was that the additional NO would allow for more collisions between reactants, causing the production of more NO\textsubscript{2} and the consumption of some of the NO and O\textsubscript{2}, until the concentrations of all species level off due to the simultaneous concurrence of both the forward and reverse reactions. When graphing this event, it was expected that a spike in the concentration of NO was noted (an instantaneous increase in NO concentration), the new equilibrium concentration of NO was higher than it was at the initial equilibrium but lower than its adjusted value, the concentration of O\textsubscript{2} was lower than it was at the initial equilibrium, the concentration of NO\textsubscript{2} was higher than it was at the initial equilibrium, and no simple, arithmetic relationship between reactants and products was indicated or shown. These were the criteria for a response obtaining an SU (sound understanding) coding. A PU (partial understanding) coding was applied to responses and graphs that did not include all these criteria. For all concentration graphs, the x-axis is concentration, and the y-axis is time (see Appendix J for the coding assigned to each teacher’s predictions, explanations and graphs).

Twelve of the teachers (92%) correctly predicted the overall changes to the concentrations over time, but when asked to explain their predictions, only five of those teachers (B, E, J, K, and L; 42%) gave complete explanations that included the fact that the new equilibrium concentration of NO would be higher than it was at the initial concentration, or that the additional NO would not be entirely consumed. Teachers E, and J also offered an explanation based upon the equilibrium constant or reaction quotient, Q:

SG: And why would those concentrations change?
E: To re-establish equilibrium. To re-establish K.

J:…with the number of particles that we have…now you have more NO to collide with the O\textsubscript{2} and produce more of the product. I guess like a Q, a mathematical reason would be you’re… decreasing Q. So then the reaction- It’s going to shift to the right to re-establish equilibrium.

An additional 2 teachers (H and I) drew graphs that included the fact that the additional NO would not be entirely consumed, demonstrating the benefit of the graphing and reflection about the graphs as important for obtaining a deeper understanding of the teachers’ conceptions. In fact, teacher I initially said that the NO would revert to its initial equilibrium concentration, but through drawing and discussion changed her mind to a different conclusion:
I: …So we have a spike here[NO], immediately, and then as time goes on, we're using it up, and we re-establish equilibrium…You're going to add it in initially here, so you have a new concentration at equilibrium, and over time it's being used up and brought back down to sort of to the same spot it was initially. Oxygen is being used up a little bit, and then it is…going to be re-established at some point…And...you are going to be producing NO[2], so you make a little bit more of it, and then, at some point, you should re-establish equilibrium. That is...fairly close to where it started, I would think.

SG: When you say fairly close to where you started, what does that mean?

I: A good question…I really don't know the answer, because Le Châtelier says if you have an equilibrium and you stress an equilibrium, stress a reaction equilibrium, you're going to...force the reaction one way or the other to relieve the stress, and bring things back to close to normal. But they never say bring them back to normal. So I'm going to say close to normal.

SG: Close to normal. So when you say 'close to normal'?

I: Or close to original. How about that?

SG: Close to original. All right. So, I would like you to compare...the concentrations at the original equilibrium to the concentrations at this next equilibrium.

I: This should be lower than this.

SG: Okay. That's oxygen?

I: Oxygen. Nitrogen monoxide should be a little higher. And nitrogen dioxide should be a little higher.

At completion, seven of the teachers’ graphs received an SU coding (54%), an example of which is shown in Figure 17.

Figure 17. SU-coded concentration graph for the addition of NO to the system at equilibrium. [Teacher E]

For six of the teachers, though their predictions and explanations did not contain obvious errors, their graphs demonstrated significant and varied alternative conceptions. Teachers A and G drew graphs that initially looked correct, with a spike in NO concentration and its subsequent decrease. However, when questioned about the relationship between the initial equilibrium concentration of NO and the concentration of NO after the re-establishment of equilibrium after
the addition of more NO, both said that it was not possible to ascertain whether the new equilibrium concentrations would be higher, lower, or the same as the initial equilibrium value, without mathematical calculations:

SG: ...How does this concentration of NO compare to the concentration of where it was at the first equilibrium?
G: My graph is showing that it has gone up from this point of equilibrium. I guess, not thinking in terms there being enough information as to where the concentrations are going to end up at this new point. I just was representing this one decreasing, O₂ decreasing. Not thinking from the standpoint of...would this amount be higher than at this point in equilibrium...That's how it's represented.
SG: But what is your gut feeling for why that would be? The fact that it would be higher?
G: ...I mean, just depending on how much- how much you added. It's hard to tell where its going to end up.
SG: So, you're saying that you've drawn it as higher, but it could be equal or lower?
G: Um...yes. Yes.

A: ...It's hard-it's hard to tell without solving it mathematically...It's hard. It's hard for me to tell...Only mathematically would I be able to tell you what the concentrations are...So I can't- I can't tell you that.

Along the same lines, a second alternative conception was demonstrated by the graph drawn by teacher D, who indicated that the re-established equilibrium concentration of NO would be lower than it was at the initial equilibrium, since the reaction would move in the forward direction to achieve equilibrium. His graph (which is mislabeled and corrected) is shown in Figure 18.

![Figure 18. PU-AC-coded concentration graph for the addition of NO to the system at equilibrium. [Teacher D]](image)

A third alternative conception to be uncovered during this exercise was that, even after the addition of NO, at equilibrium, the concentration of NO would decrease to the point that it was stoichiometrically equal to the concentration of NO₂. This was expressed by teacher F:
F: …over time, I would expect that [NO] would come back down a little bit. I would expect that the NO$_2$, with the mole ratio, should come back up and meet that. And I would expect my… O$_2$ to decrease. Because I didn't change that concentration.

The graph drawn by F is shown in Figure 19.

![Figure 19. PU-AC-coded concentration graph for the addition of NO to the system at equilibrium. [Teacher F]](image)

A fourth alternative conception was uncovered during the graphing task with teacher M. According to her graph and the explanation of what she drew, after the NO$_2$ increased, and the O$_2$ decreased, both of those species would revert to their initial equilibrium values. This graph is shown in Figure 20.

![Figure 20. AC-coded concentration graph for the addition of NO to the system at equilibrium. [Teacher M]](image)

Last, teacher C drew a graph that was inconsistent with his initial explanation, as well as his explanation of the graph. His graph is shown in Figure 21 and seems to suggest that the
concentration of NO increases in a similar way to NO\textsubscript{2} but does not decrease at all. This is not how C explained the event:

![Figure 21. AC-coded concentration graph for the addition of NO to the system at equilibrium. [Teacher C]](image)

\textbf{SG}: Okay. And so, when we're done, the concentration of the NO\textsubscript{2} will be higher than it was at the original equilibrium. The NO will be higher than it is at the original equilibrium-

\textbf{C}: No.

\textbf{SG}: No? I'm sorry.

\textbf{C}: ‘Cause, again, if you're back at equilibrium, the concentrations have to be constant. So .. we have to be back to two moles. If we're doing concentration based on moles, right, then it's going to have to go back to two moles.

Either way, the graph and the comment both describe alternative conceptions. Overall, 31% of the graphs, and 46% of the explanations contained alternative conceptions.

**Addition of Reactant – changes in rate**

After discussing the changes to concentration upon the addition of NO, teachers were asked to predict, explain, and then graph what would happen to the rates of the forward and reverse reactions from the time the additional NO was added to system at equilibrium, until the time that equilibrium was re-established. The expected prediction was that the rate of the forward reaction would instantaneously increase upon the addition of NO, and then decrease. The rate of the reverse reaction would increase to meet the rate of the forward reaction, at which time the rates of both reactions would be equal, constant, and higher than they were at the initial equilibrium. For the explanation as to why this would occur, the simplest expected response was that the additional NO would instantaneously cause more collisions among reactants resulting in an instantaneously higher forward rate, and the reverse rate would begin to occur as the forward reaction occurred. A higher rate at the re-establishment of equilibrium is due to there being more overall particles in the system, and therefore more overall collisions. When graphing the approach to equilibrium, a spike in the rate of the forward reaction was expected, followed by its subsequent decrease, and the rate of the reverse reaction would be expected to increase and meet the forward rate at the new equilibrium. These were the criteria for a response obtaining an SU
(sound understanding) coding. A PU (partial understanding) coding was applied to responses and graphs that did not include all these criteria. For all rate graphs, the x-axis is rate, and the y-axis is time (see Appendix K for the coding assigned to each teacher’s predictions, explanations and graphs).

12 of the thirteen teachers (92%) immediately and correctly predicted that the rate of the forward reaction would initially increase upon the addition of more NO. Few of the teachers indicated that the forward rate would subsequently decrease, not until they drew their graphs. An example of an SU-coded graph is shown in Figure 22. When asked about the effect of the NO on the rate of the reverse reaction, and how the new equilibrium rate compared to initial equilibrium rate, they made mixed predictions and explanations, and nine of the teachers (69%) expressed ideas that constituted combinations of six different alternative conceptions. An alternative conception held by six teachers (46%) was that upon re-establishing equilibrium after the addition of NO, the forward and reverse rates would become equal to what they were at the initial equilibrium. This alternative conception was held by teachers F, G, H, J, K, and L:

![Figure 22. SU-coded rate graph for the addition of NO to the system at equilibrium. [Teacher B]](image)

- K: So, it's showing that the forward reaction, initially…the rate increases, and in rate, and then levels off to be the same rate as the forward reaction.
- SG: Okay. And comparing the rate at equilibrium here, [referring to the final equilibrium] compared to the rate at equilibrium when we started, is that higher? Lower? The same? I can't tell from your picture.
- K: Here, they're about the same…I would say that they are about the same.
- SG: Okay. When you say, 'about the same'...
- K: Well, within experimental certainty.

- SG: And, how do the rates compare at the first equilibrium and the second equilibrium?
- H: ...I don't know. I mean, the concentrations are different. So... maybe the same.
- SG: So, this point here, the rate is the same as it was over here?
- H: Sure. [laughs] I don't know.

- SG: And so, where they meet now, is it equal, higher or lower than it was before?
**G:** Um...it should be the same. So, these should be the same points.

The graph drawn by **K** is shown in **Figure 23.** Teacher **D** also initially believed that, but after working through the graph, came to the correct conclusion that the final rate would be higher. Teachers **F,** **G,** and **L** suggested that the reason that the rate would revert back to the original rate was because the temperature or the equilibrium constant hadn’t changed:

**F:** …Because once the equilibrium dynamics have been re-established, if temperature and pressure are the same, the rate of change should be back to where it was, because *K* hasn’t changed.

![Figure 23. AC-coded rate graph for the addition of NO to the system at equilibrium. [Teacher K]](image)

**G:** I’m thinking back in my head, in terms of we haven’t changed the…temperature, so I’m just thinking for a second if...I’m finishing at the right rate. I’m just representing forward rate going up. Reverse rate going down.

**L:** …if right when you add the NO then let's say there's a jump in the forward....But then eventually…if this is the rate that it was before…then I'm thinking the [rate of the] forward reaction is going to have to re-establish. Because the temperature still hasn't changed.

**L:** I made it the same just because I haven't changed the temperature...And the *K* is still the same.

In addition, teacher **L** maintained that the *both* the rates of the forward and reverse reactions would instantaneously increase. Teacher **J,** after some discussion, arrived at the correct conclusion that, since there were more particles at equilibrium, the rate should actually be higher. **Figures 24** and **25** show the graphs drawn by **L** and **J:**
Another alternative conception, maintained by four (31%) of the teachers (C, G, H, and K), was that the forward reaction rate increases but the reverse reaction rate decreases before becoming equal at equilibrium:

SG: … if I increase the NO by a certain amount, what will happen to the rate of the forward and the rate of the reverse reactions?...
C: The rate of the forward would increase, and the rate of the reverse, would initially decrease, but then eventually they'd go back into being equal.

K: So, the forward reaction would increase. The rate would increase.
SG: And the reverse?
K: And the reverse would decrease and then, eventually, come together and re-establish equilibrium.

Teacher F said just the opposite, that the reverse rate would increase and the forward rate would decrease. Teacher H initially said that the reverse rate would decrease, but then expressed uncertainty. She then drew the reverse rate as decreasing (Figure 26). When pressed further, she said that it might remain the same, but came to this conclusion in a somewhat frustrated way:

H: If you add NO, the forward reaction increases.
SG: Okay. And the reverse reaction?
H: Um, temporarily decreases...
SG: Okay. So.. could you explain to me why you predicted that?
H: Because when there's more NO- NO is a reactant of the forward reaction. So, there are more molecules for collisions.
SG: …And the reverse reaction decreasing. Why would that be?
H: Um...Because...If- How would I explain that? ... [long pause] ... I don't know that it would even slow down, though. But it's certainly not going to increase, temporarily, while the forward reaction is increasing until equilibrium is re-established. I don't really know what happens to the reverse reaction...Never
thought about that. The forward reaction increases, cause there's more NO...Um...Yeah, I mean, it's not really ch- It's going to be changing the amount of NO\textsubscript{2}, which will eventually bring the reverse reaction back up so that it's equal to the forward reaction.

after drawing,

SG: …why did you draw it in this particular way?
H: Only because I know that they have to be equal again. Otherwise equilibrium is not re-established. So it's going to go up. Eventually, it's going to- It's going to temporarily increase as you add NO, but then it's going to slow down again as the reverse reaction kicks back in. Until they become equal.
SG: And you have the reverse reaction, like, doing the opposite, going down and then coming back up again?
H: Sure. Or it can go straight across. I really don't know.

Teachers C, F, and G initially drew graphs that had the one rate increasing and the other rate decreasing but realized after some reflection that the two lines did not meet and changed their graphs to reflect that the forward and reverse rates had to be equal at equilibrium. The graphs drawn by F and G are shown in Figure 27 and Figure 28.
Three teachers (I, J, and K) maintained that when the NO was added, the reverse reaction would not occur until after the forward reaction had completed or had proceeded to a certain point:

I: …the rate of the forward reaction should increase...and the...rate of the reverse reaction should stay the same until some time when you make a lot more NO₂…the reverse reaction, in my mind, shouldn't change until there's enough nitrogen dioxide to warrant the same thing in reverse, the decomposition reverse.

Teacher C understood that the forward rate would increase and that the rates must be equal at equilibrium but decided that the only way to have the that occur was to have the rates increase together. The graphs drawn by I and C are shown in Figure 29 and Figure 30.

Teacher M was the only teacher to predict that the rates of the forward and reverse reactions would remain unchanged upon addition of NO. She held two alternative conceptions. First, she maintained that a shift predicted by Le Châtelier’s principle has nothing to do with the rates of reactions. Second, she said that since there was no change in temperature, neither the rate of the forward nor the rate of the reverse would be affected:

M: So this is a Le Châtelier's shift, but it's only in terms of concentration. So there'll be no change in the rate.

When questioned about her graph, which was simply a straight, horizontal line:

M: Because now you reached equilibrium. You didn't disturb the temperature. All you did was change a concentration. So, nothing's going to change the rate until you change the temperature.

SG: ...Without changing the rate, how do you get the shift?

M: Well, the shift is only in relative quantities. So, the quantity shifted has nothing to do with the rate. I know that it's spoken of as a temporary increase in the rate of the forward, but I don't really like that term, because if you talk about
rates changing then you're really implicating a temperature change. So, as far as my students go, I tell them to never touch the rate unless the temperature changes.

This exchange demonstrated how teachers superficially use Le Châtelier’s principle, not as an algorithm, but as a means of explaining why shifts would occur. Overall, there was quite a high number of alternative conceptions expressed during this part of the interview, and different teachers held different combinations of them.

**Increasing Temperature – changes in concentration**

The discussion then turned to considering an increase of the temperature to a system at equilibrium. Teachers were asked to predict, explain, and then graph how the concentrations of each of the three species would be affected when the equilibrium system was disturbed by the increase of the temperature, and was allowed to re-establish equilibrium. The expected prediction was that the concentrations of the NO and O\(_2\) would increase, and the concentration of the NO\(_2\) would decrease until equilibrium was re-established, at which time the concentrations of each of the species would remain constant. For the explanation as to why this would occur, the expected response was that the increase in temperature would allow for more kinetic energy and collisions between reactants and products alike, along with an explanation of how that would cause the reverse reaction to occur at a higher rate then the forward reaction (such as a description of the Arrhenius equation or how a Boltzmann distribution changes with temperature), until the concentrations of all species level off due to the simultaneous concurrence of both the forward and reverse reactions. When graphing this event, it was expected that an increase in the concentrations of NO and O\(_2\) and a decrease in the concentration of NO\(_2\) would be noted, that the concentrations had been changed from the initial equilibrium, and no simple, arithmetic relationship between reactants and products was indicated or shown. These were the criteria for a response obtaining an SU (sound understanding) coding. A PU (partial understanding) coding was applied to responses and graphs that did not include all these criteria. For all concentration graphs, the x-axis is concentration, and the y-axis is time (see Appendix L for the coding assigned to each teacher’s predictions, explanations and graphs).

Unlike the previous section, where NO was added to the system, fewer alternative conceptions were uncovered for this event, but what was discovered with respect to the teachers’ understanding of this change was significant. Although every teacher could predict what would happen to the concentrations of NO, O\(_2\), and NO\(_2\), only one teacher (B) could sufficiently explain why more reactants would be produced when the temperature of this system was increased:

**B**: Any reaction is going to go faster at a higher temperature because more particles will have energy greater than activation energy. But the effect is going to be greater on the reaction with the higher activation energy. And…that’s the endothermic direction.

**SG**: Why?

**B**: Why? The way that I make sense of that...basically is...based on a Boltzmann distribution.

**SG**: Can you explain that?

**B**: Yes. So, if you think about...um...should I draw? Am I allowed to draw to explain it? Or do you just want me to just [**SG**: No, draw!] Okay. So, if you think about how Boltzmann distribution changes with temperature ... [drawing, Figure...
... That's my low temperature. That's my higher temperature...and, then, suppose I had - [labeling] That's my one activation energy. That's the second activation energy. The one with the higher activation energy is going to have a greater change in the number of particles with \( E \) greater than \( E_a \). That's how I understand that.

Figure 31. Drawing used by Teacher B to describe temperature changes to a system.

Three other teachers (A, D, and J) suggested that the increased energy from the temperature increase would provide more particles sufficient energy to overcome the activation energy of the reverse reaction, but experienced difficulty when trying to explain why that wouldn’t also be true for the forward reaction. (It is, but the endothermic reaction is affected to a greater extent.). For example:

A: When you raise...the temperature of this system, you're going to increase the collisions of both the forward reaction and the reverse reaction. But the reverse reaction, which has a higher activation energy, is going to be slower. Generally speaking, the higher the activation energy the slower the reaction. When you increase the temperature, you don't change the activation energy. Nothing changes the activation energy. But, when you increase the temperature, you have more molecules that have enough kinetic energy to reach the activation energy and reach the activated complex...But wait a second [laughs]. If I increase the temperature, then I also increase the number of molecules here [referring to the forward reaction] that can...reach the activated complex...

The remaining nine teachers (69%) treated the heat in the equation as a product and utilized Le Châtelier’s principle to explain the production of more reactants. Some examples:

SG: I guess my question is, why? Why would it be going in this direction, when you raise the temperature, instead of the other direction?
E: To alleviate the stress, that's going to be caused by the exothermic reaction adding energy. You need to consume the energy, which means it will shift left. And to get back to lower energy.
F: Well, it's an exothermic reaction. So, again, I don't have the- If there's a better answer, I hope you'll share that with me. But... if you have an exothermic reaction, raising temperature...has the same effect in terms of shifting the reaction, as if you changed concentration. If I increase the concentration, you'll drive the reaction in reverse.

G: ... the system is at a particular balance point at equilibrium. So by increasing the temperature, you are...at that point going to upset the point of equilibrium. So in order to establish a new equilibrium point, the endothermic reaction is going to be favored in order to absorb any additional heat that was added to the system.

I: …if you're moving away from the heat...If you're doing the endothermic reaction, you will drop the amount of heat there, and bring things back towards the initial starting point. Just like if you increase the concentration here, you're going away, because you re-established equilibrium by decreasing the amount that was out of whack.

SG: …So you're treating the heat as a product, essentially.

I: That's how I think of it.

L: …Well, the way I teach it, is I treat the heat energy, and since temperature's a measure of the average kinetic energy. So, if you increase the temperature, you're adding kinetic energy. So, if you're adding kinetic energy, then it's the same as if I'm adding a product or a reactant or I'm increasing the pressure. I've stressed out, and I've added or increased to a side. So, it's got to shift to the other side.

Most of the teachers (85%) could accurately draw the graph for this event, an example of which is shown in Figure 32. The other two teachers (C and M) shared the identical alternative conception that, although the concentrations of NO, O2, and NO2 would change initially as predicted, they would return to their initial values once equilibrium was established:

C: I think that's [NO2] going to go down, and then it's going to go back to it's original...Yeah, because the concen … We're not adding anything. Not like initially when you added more NO. All right, so basically you have the same amounts...So that's [NO] going to go up, but then eventually that's going to go back down to where it was.

SG: Okay. So .. the equilibrium concentrations will be the same as they were at the initial one?

C: Yes.

M: …There'd be a shift spike...And we didn't add any other reactants. So I'm just gonna, I'm just gonna pop it up and then...have it come back. It's at the new temperature, but that's just a rate thing. So, I'll pop my guy up, here...and I'll have this guy pop down...

SG: And…the equilibrium concentrations here, compared to where they were at the last equilibrium?
M: Well … we didn't add or remove any products or reactants. So .. they're going to be the same.

During that last exchange, M makes a distinction between kinetics and equilibrium. C and M produced identical graphs; one is shown in Figure 33. Once again, the graphs uncovered an alternative conception that would not have been uncovered with just the prediction or explanations alone. Though just one major alternative conception was uncovered, the teachers’ use of Le Châtelier’s principle not just to predict, but to explain, the change in species’ concentrations was frequent.

![Figure 32. SU-coded concentration graph for the increase in temperature of the system at equilibrium. [Teacher B]](image1)

![Figure 33. AC-coded concentration graph for the increase in temperature of the system at equilibrium. [Teacher M]](image2)

**Increasing Temperature – changes in rate**

After discussing the changes to concentration upon the increase of the temperature of the system, teachers were asked to predict, explain, and graph what would happen to the rates of the forward and reverse reactions from the time the temperature was increased until the time that equilibrium was re-established. The expected prediction was that the rate of both the forward and reverse reactions would instantaneously increase, though the increase would be higher for the reverse reaction. Subsequently, the reverse reaction rate would then decrease and the forward rate would increase until the rates of both reactions would be equal, constant, and higher than they were at the initial equilibrium. For the explanation as to why this would occur, the simplest expected response was that the increase in temperature would instantaneously cause more collisions among reactants and products, resulting in instantaneously higher rates for both reactions. When graphing the approach to equilibrium, a spike in both rates was expected, but higher for the reverse reaction, and the rate of the reverse reaction would be expected to decrease and meet the forward as it increased further to attain the new equilibrium rate. These were the criteria for a response obtaining an SU (sound understanding) coding. A PU (partial understanding) coding was applied to responses and graphs that did not include all these criteria. For all rate graphs, the x-axis is rate, and the y-axis is time (see Appendix M for the coding assigned to each teacher’s predictions, explanations and graphs).

As with the rate discussions accompanying the increase in NO to the system at equilibrium, the rate discussions surrounding the increase in temperature uncovered several alternative
conceptions, and teachers had different combinations of them. All of the teachers correctly predicted that the rate of the reverse reaction would increase, but that is where the similarity between them ended. 7 teachers initially predicted that both rates increased (A, B, E, I, J, L, and M). Of the remaining six teachers, one (D) predicted that the reverse would remain constant for some time and then increase, and five (C, F, G, H, and K) initially predicted that the rate of the forward reaction would decrease, which is a common alternative conception:

D: The rate of the reverse will increase, and the rate of the forward will...initially remain the same, but eventually it will increase, but not as much as the rate of the reverse.

D: ... Well, we didn't take away any of the reactants. So, initially there should be no change in the rate of the forward, initially, but eventually it should start to increase again...

SG: …If I increased the temperature, what will happen to the rate of the forward reaction? What will happen to the rate of the reverse reaction?
F: …The rate of the forward reaction is going to go down, and the rate of the reverse reaction will go up.
SG: And why do you think so?
F: Well, if I'm driving the reaction in reverse by raising temperature, then if it's favored- if I'm more likely to go in reverse, then the reverse reaction is favored during that timeframe. So, the reverse reaction has to be increased. So, if that has to be favored, rate is faster versus that, until the new equilibrium is established.

G: … the rate of the reverse reaction will increase, and the rate of the forward reaction will decrease from the initial point that you increased the temperature.

K: The reverse would increase. And...forward would decrease and then eventually it would re-establish that equilibrium and become equal.

Later, teacher J decided that the rate of the forward had to decrease, teacher D decided that the forward rate would increase, and teacher H decided that both rates would increase.

Of the teachers who initially expressed that the rates of the forward and reverse rates would both increase only A, B, and L initially predicted that the rates would be different. The other teachers only expressed this as they were drawing the graphs. Overall, eleven teachers understood that the rates of the forward and reverse reactions would initially be different. Teacher M, however, predicted that the rates of both reactions would increase together:

M: Rates always go up when the temperature goes up. So, they're going to go up equally, after this stress...The heat causes...all the kinetics activity to increase. And so the rate of all reactions increases at a higher temperature.

M drew a graph consistent with her explanation, shown in Figure 34. Teacher H drew a graph similar to M’s but admitted that she was unsure. She initially suggested that the forward rate
would decrease. However, as the discussion continued, she felt that it was not possible for the rate of the forward reaction to decrease, so she decided that both rates would increase together:

**H:** Well, they would both increase .. maybe, and both stay the same? I'm...really making up stuff, here, because...I'm thinking two things at once. Like, one side of me is thinking that the system is moving to the left. Of course, the reverse reaction is increasing in rate, but then at the same time, all molecular collisions are increasing. So, wouldn't they both be increasing in rate? I don't know.

![Figure 34. AC-coded rate graph for the increase in temperature of the system at equilibrium. [Teacher M]](image)

Another way that these teachers differed, was in their analysis of where the final equilibrium rate would lie. Ten teachers (A, B, D, E, F, H, I, J, L, and M) correctly indicated that the final equilibrium should be higher than the initial equilibrium, though J would later decide that the final equilibrium should be the same as the initial equilibrium, and alternative conception also maintained by teacher C:

**C:** And so, the forward reaction will eventually go down. Reverse reaction initially goes up, right? And then again, eventually they will go back to being the same.

Teachers G and K had the alternative conception that the final rate at equilibrium should be lower than the initial equilibrium rate, since the equilibrium constant was lower:

**SG:** And the final equilibrium, compared to the initial equilibrium?

**K:** …looking at it more closely now, I would say that it[the rates] should probably be a little bit lower than originally. Because when this re-establishes... you're going to have a new equilibrium constant and a new ratio of components of the reaction. And that would favor the production of the two reactants and less of the products.

**G:** …And I’m going to say that, this new [equilibrium rate]- is a little lower than the one before.

**SG:** And why would that be the case?
**G:** With the change in temperature. So we- we’re actually changing the point of equilibrium.

**SG:** Okay. And why did you choose that it was lower rather than higher?

**G:**...Let me look back at my concentrations, see if I’m consistent...if I’m going to be consistent with my concentrations at this new equilibrium point, where my NO\(_2\) is lower than it was before. My NO and my O\(_2\) higher than they were before, based on my equilibrium constant…my K is a little lower...So that’s why I put it a little lower.

None of the teachers drew a graph that was consistent with what would happen when the temperature is increased. A graph drawn by the researcher, shown in **Figure 35**, includes instantaneous increases in both rates, and an equilibrium rate that is higher than the initial rate.

![Figure 35](image)

**Figure 35.** Characteristics of a rate graph for the increase in temperature of the system at equilibrium.

By the end of the discussion about how rate was affected by the temperature increase, graphs closest to being accurate fell into two categories. First, teachers B, D, and E drew graphs that showed an instantaneous increase in the reverse reaction, and an increase in the forward reaction, though not an instantaneous one. Their graphs had a final rate that was higher than the initial rate. An example of this graph is shown in **Figure 36**. Second, teachers A, I, and L drew graphs with no instantaneous increase, but the forward and reverse rates were depicted as dissimilar. An example of this type of graph is shown in **Figure 37**. These types of graphs were coded as PU-AC, since they did not have the instantaneous increase in one or both of the rates.

![Figure 36](image)  ![Figure 37](image)

**Figure 36.** PU-AC-coded rate graph for the increase in temperature of the system at equilibrium. [Teacher D]

**Figure 37.** PU-AC-coded rate graph for the increase in temperature of the system at equilibrium. [Teacher A]
The rest of the graphs were coded AC, for the alternative conceptions that (a) the forward rate would decrease, (b) the rates would increase together, and (c) the final equilibrium rate being lower or equal to the initial rate. Examples of these graphs are shown in Figure 38 and Figure 39.

Another statement was made by M, defining the separation of kinetics and equilibrium in her mind:

M: Now the temperature will also make everything move faster, you know, kinetically. But if I’m treating this as an equilibrium problem, I’m isolating my interest in what the heat does to the shift.

This statement was similar to the one she made while discussing the concentration changes in the previous questioning.

**Decreasing Volume – changes in concentration**

Next, the teachers discussed the concentration change that would accompany a change in the volume of the system at equilibrium. Teachers were asked to predict, explain, and then graph how the concentrations of each of the three species would be affected if the equilibrium system was disturbed by a decrease in the volume, and then was allowed to re-establish equilibrium. The expected prediction was that the concentrations of the NO and O₂ would decrease, and the concentration of the NO₂ would increase until equilibrium was re-established, at which time the concentrations of each of the species would remain constant. For the explanation as to why this would occur, the simplest expected response was that the decrease in volume would cause an increase in the partial pressure or the concentration of all species, allow for more collisions between reactants and products alike, along with an explanation of how that would cause the forward reaction to occur at a higher rate than the forward reaction (such as a description of the equilibrium constant or the rate law), until the concentrations of all species level off due to the simultaneous concurrence of both the forward and reverse reactions. When graphing this event, it was expected that an instantaneous increase in the concentrations of all species was noted, as
well as a subsequent decrease in the concentrations of NO and O₂ and increase in NO₂. These were the criteria for a response obtaining an SU (sound understanding) coding. A PU (partial understanding) coding was applied to responses and graphs that did not include all these criteria. For all concentration graphs, the x-axis is concentration, and the y-axis is time (see Appendix N for the coding assigned to each teacher’s predictions, explanations and graphs).

Once again, the prediction caused no problems for the participants, all of whom correctly identified what would happen to each of the species. However, many of teachers used Le Châtelier’s principle as an explanation of why the forward reaction would occur more often in the approach to establishing a new equilibrium:

C: Okay. So, since we have three moles here and two moles here, right? If you increase the pressure, your favor the lower number of moles. So, if you increase the pressure, or decrease the volume is what you initially said. But I going to assume I can say them both. Right? So, if you increase the pressure, the forward reaction is going to go slightly faster.

F: …Well I have a... three-to-two ratio of moles. So if I raise pressure, I have to re-establish the pressure by producing more product which has less moles of gas, since…pressure is a function of the moles of gas present. So I need to decrease the number of moles present to lower the pressure back to the equilibrium pressure.

Most of the teachers (85%) focused on the change in pressure that would accompany the decrease in volume, and therefore failed to mention that the concentrations would all instantaneously increase. In fact, only one teacher, B, drew the expected graph, shown in Figure 40. The majority of the other teachers (C, D, E, F, G, H, I, J, K, and L) drew similar graphs that did not include the instantaneous spike in concentrations. An example of that graph is shown in Figure 41. Since all of these teachers did include the spike in NO on the concentration graphs for when NO was added to the system, and both of these events (addition of NO and decrease in volume) translate to an instantaneous increase in NO concentration, it demonstrates a disconnect between the two events in the minds of these teachers, since they all referred to the volume decrease as a change in pressure, and not concentration.

Figure 40. SU-coded concentration graph for the decrease in the volume of the system at equilibrium. [Teacher B]

Figure 41. PU-coded concentration graph for the decrease in the volume of the system at equilibrium. [Teacher K]
Three teachers demonstrated other alternative conceptions with respect to the decrease in volume. First, teacher M did consider the instantaneous changes in concentration, but thought that the increase in NO$_2$ and the decrease in NO and O$_2$ concentrations were the instantaneous change, and that the system would re-establish equilibrium by returning the concentrations to what they were before the decrease in volume:

**M**: This is just another Le Châtelier's stress. So, you treat it like anything else. So, the NO$_2$ is going to have a temporary spike, and then come back down. So, it's just pressure, we didn't add any other reactants or products. So, we'll have a spike up. We'll come back down.

**SG**: To where it was before?

**M**: Yeah.

The graph that M drew is shown in **Figure 42**. Teacher L also felt that the concentrations should revert to the original concentrations upon the re-establishment of equilibrium:

**L**: But there's no temperature change, so they have to end up…if I'm going to let that be indicative of the K, then they have to end up at the same place.

A second alternative conception was expressed by teacher A, who maintained that all of the concentrations, including NO$_2$ would decrease after their instantaneous increase. Her graph is shown in **Figure 43**. She maintained this conception, even after she was questioned about it:

**SG**: Okay. So, just to explain what your pictures are. You suddenly go up. And then this [NO$_2$] is going to decrease?

**A**: Yeah.

![Figure 42. AC-coded concentration graph for the decrease in the volume of the system at equilibrium. [Teacher M]](image)

![Figure 43. AC-coded concentration graph for the decrease in the volume of the system at equilibrium. [Teacher A]](image)
Decreasing Volume – changes in rate

After discussing the changes to concentration upon the decrease in volume, teachers were asked to predict, explain, and graph what would happen to the rates of the forward and reverse reactions from the time the volume of the system at equilibrium was decreased, until the time that equilibrium was re-established. The expected prediction was that the rate of both the forward and reverse reactions would instantaneously increase, though the increase would be higher for the forward reaction. Subsequently, the forward reaction rate would then decrease and the reverse rate would increase until the rates of both reactions would be equal, constant, and higher than they were at the initial equilibrium. For the explanation as to why this would occur, the simplest expected response was that since the decrease in volume instantaneously increased the concentration of all species by the same factor, the collisions between species would be disproportionately affected, increasing the rate of the forward reaction more than the reverse reaction. When graphing the approach to equilibrium, a spike in both rates was expected, but higher for the forward reaction, and the rate of the reverse reaction would be expected to increase and meet the forward as it decreased to attain the new equilibrium rate. These were the criteria for a response obtaining an SU (sound understanding) coding. A PU (partial understanding) coding was applied to responses and graphs that did not include all these criteria. For all rate graphs, the x-axis is rate, and the y-axis is time (see Appendix O for the coding assigned to each teacher’s predictions, explanations and graphs).

Once again, the teachers in the study had a more difficult time predicting and explaining the rate changes when the volume was decreased than they did with the concentration changes, and more alternative conceptions were identified in this part of the interview. Only five teachers (38%, A, B, D, E, and I) correctly predicted that both rates would increase when the volume of the system was decreased. Of the remaining teachers, all but M predicted that the reverse rate would decrease, a common alternative conception. M predicted that the rates would remain the same, since the temperature had not been changed, an alternative conception she had expressed earlier in the interview. A sample response from each group shows the difference in conceptions:

**B:** .. So, I'm predicting that, at the moment that we've...decreased the volume, all the rates are going to increase, but that the rate for the forward reaction is going to increase more than the rate for the reverse reaction, to start.

**J:** …the forward reaction would increase initially, but then level off and the reverse would decrease a little and then level off.

**M:** …once you're back to equilibrium, since you didn't change the heat, it'll be the same rate.

Of the five teachers who correctly predicted that both rates would increase, only B drew a graph consistent with the idea that both rates would instantaneously and disproportionately increase, and how the new equilibrium was attained. Her graph is shown in Figure 44. Teacher D drew an instantaneous increase in the forward reaction rate, and just an increase in the reverse rate. His graph is shown in Figure 45.
Teachers A and I drew similar graphs that depicted a disproportional increase in both rates, but without either rate instantaneously increasing (Figure 46). These graphs were coded as PU-AC, since they did not show the immediate increase in rate. More commonly, the teachers drew graphs showing an increase in the rate of the forward and a decrease in the rate of the reverse, followed by a return to the initial rate before the change. This alternative conception was described by six of the teachers, and a sample graph is shown in Figure 47. The consensus was that since the temperature had not changed or that the equilibrium constant had not changed, the rate equilibrium should be the same:

SG: And how does the rate at the new equilibrium compare to the rate at the old equilibrium?
F: Well...At t3[after T change], I felt the rate was higher than at t2 [before T change, after NO addition], because I was at a new temp, but at t4 [after V decrease], I'm going to say, if the temperature is still the same as at t3, that rate should be the same, because I'm still at the same temperature.

L: …if I'm going to let that be indicative of the K, then they have to end up at the same place.
A final alternative conception identified during this task was that the rate of the reverse reaction would remain constant, an idea held by teacher L, whose graph is shown in Figure 48:

L: Initially, it [forward rate] gets a bump, and then it, initially just increases, and then it slows down and comes back to where it was… And the reverse could just more or less stay where it is.

Conceptions Regarding the Role of a Catalyst

The teachers were then asked about the changes that would take place in concentration and rates when a catalyst was added to the system at equilibrium. All of the teachers were able to correctly predict, explain and graph that the concentrations of all species would remain constant when the catalyst was added, since the system was already at equilibrium and the catalyst would increase the rate of the reaction. A representative graph, drawn by all the teachers, is shown in Figure 49.
Two alternative conceptions, however, were expressed by the teachers when asked to predict, explain, and graph what would happen to the rates of the forward and reverse reactions when the catalyst was added. A complete response, including the statements that the rates of both reactions instantaneously increase together, was given by four of the teachers (31%, A, B, E, and M), and shown in Figure 50:

A: …you are going to speed up the rate of the forward reaction and reverse reaction with a catalyst, but you're going to speed them up equally.

![Figure 50. SU-coded rate graph for the addition of a catalyst to the system at equilibrium. [Teacher B]](image)

Teacher M did reference, once again, that the temperature did not change:

M: With the catalyst…everybody's rate goes suddenly up. Let's say you added it right here, and you didn't change the temperature, but if the temperature is still the same, then that's gonna dictate the rate. But as long as the catalyst is present and it's not a consumable. Catalyst's just there...Well, K won't change, but the rates of both the forward and the reverse will be elevated for as long as the catalyst is there.

Three of the teachers, D, H, and I, also indicated that the rates would increase together, but did not speak of or draw an instantaneous increase:

D: You've increased the rate of a forward and reverse equally because you found an alternative route to lower that activation energy…Nothing changes. Well, no, the rates change, of course. The concentrations don't. (see Figure 51)
There was some uncertainty about how the equilibrium constant fit into the scenario where a catalyst was added to the system:

H: ...But then the fact that it's [the equilibrium rate] not at the same point anymore...I guess that doesn't necessarily inform K. Like, I just, all I keep thinking about is the value of the equilibrium constant. I don't- I don't know. I really just don't know, is the bottom line, and I'm not really ashamed to say that.

[laughs]

One significant alternative conception that was expressed during the interview and graphing task was that the catalyst would increase the rate of the reaction initially, but then the rates would return to what they were at the initial equilibrium. This was expressed and drawn by three teachers, C, G, and K, who could not explain why they thought that would happen:

SG: What about the rates of reactions? What would happen to the rate of the forward and the rate of the reverse, if I add a catalyst?
K: They both would increase and then level off to be the same as what they started.
SG: And why should that be the case?
K: The catalyst only- it lowers the activation energy for both the forward and reverse reactions. So, it makes it easier for both of them to happen, but it doesn't-doesn't change [equilibrium position].

G: ... So the rates increase, but the equilibrium point...[pause]
SG: What are you thinking?
G: I’m thinking that...the catalyst is increasing the rates of both the forward and reverse...But...I’m thinking...down the line at the new equilibrium point as to...whether the equilibrium point is going to shift or not...Um...’cause I just don't remember...[long pause]...
SG: Okay. So, you're trying to figure out where it’s going to end up over here? [referring to new equilibrium line]
G: ...’Cause I just don't remember. So, I’m gonna say that...We’re gonna end up in the same equilibrium position. I don't remember. All right. I’m going to have to take a guess...But that doesn’t make sense either...

SG: What doesn’t make sense?
G: Um...The rates are- So initially, adding the catalyst, the rates- both the forward and reverse rates increase...equally. So ... I’m going to end up at the same equilibrium position, so, all right, I’m going to have to- I’m going to have to have them ending up at the same equilibrium position. So, I’m going to say, so I’m representing the rate. The rate is speeding up, and then slowing down. But it seems to be ridiculous, but- [laughs]

SG: Why is it ridiculous?
G: Because I am...because I’m trying to come up with the next way, like, if you held a gun to my head, and you needed an explanation of why adding a catalyst, the rates would increase and then would decrease again...[pause, laughs]...All right...Okay. I'll leave it there.

SG: That’s the forward and reverse?
G: Yeah.

C: I would just say it would be a straight line. That would be the forward and reverse.

SG: So, the rate would stay the same from where they were, to the same equilibrium. [C: Mmm-hmm.] Okay, and why would that be the case?
C: Um, well, hold on. [inaudible] I would say it would, for both, go up. and then maybe go back down where it originally was. Because, again, a catalyst's job is to orient those reacting particles to the correct- I like to talk about the correct angles, the correct orientation for the effective collision that you need for reaction to occur. Right? So that happens quickly, but then again you have to go back into equilibrium. So you might reach equilibrium faster with the catalyst.

An example of these graphs is shown in Figure 52.

![Figure 52](image)

*Figure 52. AC-coded rate graph for the addition of a catalyst to the system at equilibrium. [Teacher K]*
A second alternative conception was held and drawn by teacher F, who indicated that the rates would be unaffected because there was no drive to either the reactant or the product side:

SG: What will happen to the rate of the forward and the rate of the reverse when I add the catalyst?
F: It's just going to- Both will remain at the same rate.
SG: And why would that be the case?
F: Again, the catalyst is only speeding up both rates. It's not creating a favored rate.

His graph is shown in Figure 53.

Figure 53. AC-coded rate graph for the addition of a catalyst to the system at equilibrium. [Teacher F]

Conceptions Regarding the Addition of Water to the System

The last conceptual question that was asked of the participants was to predict what would happen to the system at equilibrium if water was added to it and elicited varied responses. This is not a typical question that is addressed within the equilibrium unit, which tends to focus on changes of concentration, temperature and pressure/volumes. Of the thirteen teachers, only four (A, E, J, and K) correctly predict that NO2 will react with the water. Of these four teachers, only one (E) correctly determined the consequences of adding the water – that it will no longer be an equilibrium system as NO2 is continually removed:

E: …So I'm assuming that water is going to react with the NO2, and form nitric acid, which will remove it from the system. So it's going to shift to the right. So the concentration of everything is going to drop to almost zero. So everything's going to just drop out. Because its going to keep consuming. So this is going to keep shifting right. The NO2 is going to form nitric acid .... the system is going to completely change...if you keep removing product, you're just going to keep making product until all the reactant’s consumed. At least ‘til of them[reactants] runs out, and then this is just going to keep getting removed from the system forming nitric acid, and it'll just keep dissolving in the water.

Teacher J realized that the NO2 would react with the water but decided that there would be a limit to how much NO2 would react, and therefore, a new equilibrium would be established with
the remaining species. The idea that a new equilibrium position would be established was the common idea of teachers J and K:

J: …This is what I'm thinking. That the NO₂ is going to react with the water to produce nitric acid, and that would remove it from the system. So then, NO and O₂ would move to replace it, so they would decrease. But as they replace it, it would increase. So, at this point there's no...no more reaction with the water.

SG: Okay. So, you're making an- the assumption that there's a limit to how much the NO₂ will react. [J: Yes.] Okay. And so, once that's- once that's the case...?

J: Then, um, the NO₂- the NO and the O₂ would, uh, make a new equilibrium producing more NO₂.

K: So, NO and O₂ are both decreasing. NO₂ is decreasing due to that reaction, but then it's going to...that's going to increase as a result of the NO and O₂ combining to make more NO₂.

Teacher A initially mentioned that NO₂ will react with the water, but immediately abandoned that line of thinking to fall in line with what six of the 14 teachers tended to discuss: the polarity of the three gases, and their ability to dissolve in water. This group of teachers thought about the relative solubilities of the three gases and came to rather different conclusions about what would happen. Teachers L and D both decided that, of the three gases, NO would be the most soluble, and thus removed from the system to the greatest degree, causing more NO and O₂ to be produced. However, they used different lines of reasoning:

L: …The gut feeling is that NO is more soluble than the other two. So, if I'm going to go with that, just because of its shape and polarity and so on, then it would be like removing NO more than the others. So, if I'm removing NO, then NO₂ has got to go down. More so than O₂ and NO.

D: A polar gas will dissolve, that's going to therefore decrease the overall pressure. So I think the...a semi-educated guess...I think that by adding water, even though it's not part of the reaction, it will cause the polar NO gas to dissolve, and decrease the overall pressure of the system, causing the system to shift to the reactants side.

Teacher A ultimately decided that she could not answer the question because she did not know which of the gases was most soluble, and thus could not predict the shift that would arise from the removal of the most soluble gas. Among the group of teachers who chose to discuss the solubility of the gases were B, I, and M, who all concluded that the addition of water would have no effect on the concentrations of the species because NO and NO₂ would be equally likely to dissolve (I and M), or that there would be negligible solubility of the gases (B).

A final group of teachers (C, F, G, H, and I) held to the idea that since water is not part of the equilibrium system, that there would be no change to any of the concentrations:

C: …water's not part of the reaction.
It was interesting to experience the reaction of the participants to this question. Although most were quick to admit that they were not sure what would happen, only two teachers tried to quickly move past the question by saying that they did not know the answer, or by offering only a quick response (C and H). Most seemed to appreciate the uniqueness of the question (e.g., I: Wow, that's an excellent question. Because these are gases...How did you think of this question?) and spent quite a bit of time developing their answers.

**Alternative Conceptions Outside of the Equilibrium Construct**

There were some alternative conceptions that were expressed that fell outside of the construct of chemical equilibrium and reaction rates. Most prevalent was an alternative conception regarding the mole concept. When participants were asked to draw a sub-microscopic representation of the system before and after equilibrium, 46% of the teachers in the study (teachers C, G, J, K, L, and M) drew only two molecules of NO and one molecule of O₂, representing the mole concept alternative conception that there is no difference between moles and molecules. Other alternative conceptions that were expressed during the interview were that kinetics and equilibrium are independent of one another, that Le Châtelier’s principle concerns only concentrations and not rates of reaction, that the addition of water (discussed in the last section) would have no effect on the system because water is not part of the equation, that Le Châtelier’s principle is sufficient as an explanation of what happens to a system when the temperature is changed, and the general use of anthropomorphism to discuss the reactants and products of the system.

**Summary**

In general, there were more than twice as many alternative conceptions regarding rates of reaction than regarding concentrations. The teachers had quite a bit of difficulty generating graphs for both the changes to concentration and changes to rates when the equilibrium system was disrupted, demonstrating a shallower understanding of the topics than was expected. Most of the teachers relied on Le Châtelier’s principle to guide their discussions, and their graphs were therefore drawn with the end result in mind, rather than what was happening to the system on the way to a new equilibrium position. Very few of the teachers could explain why the shifts predicted by Le Châtelier’s principle occurred, instead using Le Châtelier’s principle as the explanation for the change in position.

**4.3. Educational and Teaching Background and Alternative Conceptions**

The first and second research questions were also concerned with any relationship between the educational and teaching backgrounds of the teachers and the number and types of alternative conceptions they maintained. The following sections discuss these relationships.

**Educational Background**

The educational backgrounds of these teachers were quite diverse, ranging from a teacher with a doctoral degree in chemistry to a teacher with both bachelor’s and master’s degree in biology. Some of the teachers began their careers in the laboratory, while others knew from the
start of their education that they wanted to teach. When degrees are considered, there is only a small relationship between the probable number of chemistry courses, the number of alternative conceptions expressed, and the CECT score (Table 9). The teacher who expressed the least number of alternative conceptions during the interview and answered all of the questions on the CECT correctly, was teacher B, who has a bachelor’s degree and a Ph.D. in chemistry. On the other end of the spectrum was teacher C, who expressed the greatest number of alternative conceptions and answered only 19 of the 47 questions correctly on the CECT. This teacher earned both degrees, bachelor’s and master’s, in biology. Between these two teachers, however, there is little that represents a relationship between educational degrees and alternative conceptions in this area of chemistry. Two teachers, G and L, who had both their bachelor’s and master’s degrees in chemistry, expressed high numbers of alternative conceptions, and scored similarly on the CECT, answering 39 of 47 questions correctly. Four teachers (A, E, H, and J) had similar educational backgrounds consisting of a bachelor’s in chemistry and a master’s in chemistry/science teaching/education. These teachers scored better on the CECT (between 41 and 43) and expressed a lower number of alternative conceptions than those teachers with both degrees in chemistry. Also scoring highly on the CECT and expressing a smaller number of alternative conceptions were teachers D and I, who had bachelor’s degrees outside of chemistry (biochemistry and biology, respectively). Three teachers (F, K, and M) scored below 40 on the CECT (37, 39, and 39, respectively), and showed higher numbers of alternative conceptions (12-13). Their bachelor’s degrees included biology and chemistry, clinical laboratory science, and chemistry education, and their advanced degrees included a master’s in gifted education, a Ph.D. in neuroscience, and an M.D. in chiropractic.
Teachers were also asked if they had ever had a professional development course in chemical equilibrium, in part or in whole. Five of the teachers responded that they completed a professional development course for the Advanced Placement curriculum, which in part included a discussion of equilibrium. The professional development course did not seem to deepen their knowledge of equilibrium, as these teachers scored an average of 39 out of 47 on the CECT and maintained an average of 13 alternative conceptions.

**Certifications Held**

Table 10 shows the certifications held by the participants in the study, the number of alternative conceptions they expressed, and their scores on the CECT. On Long Island, in New York, where these teachers all work, it is quite common for teachers to hold more than one teaching certification. Holding multiple certifications renders a teacher more attractive to the school districts, which tend to pay salaries that are above the average for the rest of the state. However, a major finding of this study was that those teachers who held only one certification, in chemistry, had the highest average CECT score and the lowest number of alternative conceptions.
conceptions. Teachers **A, E, H, and J** held only a certification in chemistry, had an average score of 42 on the CECT, and maintained an average of 7 alternative conceptions. A second group of teachers (**B, D, G, K, L** and **M**) held dual or multiple certifications, with their primary certification in chemistry. These teachers had an average score of 41 on the CECT and maintained an average of 11 alternative conceptions. A final group of teachers, **C, F, and I**, held dual certifications, with their secondary certification in chemistry. These teachers had an average score of 33 on the CECT and maintained an average of 11 alternative conceptions. Hence, certification area was somewhat related to the amount of alternative conceptions these teachers maintained.

<table>
<thead>
<tr>
<th>Certification (teachers)</th>
<th>Average CECT score</th>
<th>Average number of alternative conceptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemistry Certification only (A, E, H, J)</td>
<td>41.8</td>
<td>7.25</td>
</tr>
<tr>
<td>Primary Certification in Chemistry, including those with only chemistry certification (A, B, D, E, G, H, J, K, L, M)</td>
<td>41.5</td>
<td>9.20</td>
</tr>
<tr>
<td>Primary Certification in Chemistry, excluding those with only chemistry certification (B, D, G, K, L, M)</td>
<td>41.3</td>
<td>10.5</td>
</tr>
<tr>
<td>Secondary Certification in Chemistry (C, F, I)</td>
<td>33.0</td>
<td>11.3</td>
</tr>
</tbody>
</table>

*Table 10. Average number of alternative conceptions and average CECT scores for groups of teachers with different certifications. AC=alternative conceptions expressed during interviews; CECT=Chemical Equilibrium Concepts Test*

**Classroom Experience**

A stronger relationship existed between the number of years of classroom experience teaching advanced chemistry, the CECT scores, and the number of alternative conceptions expressed. *Table 11* shows the teachers grouped by years of experience, and the average CECT scores and number of alternative conceptions. Teachers **B** and **D**, with 16 and 18 years of experience, answered most of the 47 CECT questions correctly (47 and 45, respectively), and expressed low numbers of alternative conceptions (1 and 7, respectively). Teachers who scored higher than 40 on the CECT (**A, E, H, I** and **J**) had an average of 11.6 years of experience teaching advanced chemistry, and an average of seven alternative conceptions. Another group of teachers scoring just below 40 on the CECT (**F, G, K, L**, and **M**), had an average of ten years of experience teaching advanced chemistry and an average of 13 alternative conceptions. Teacher **C**, with only six years of experience teaching AP Chemistry, answered the fewest number of CECT questions correctly (19), and maintained the largest number of alternative conceptions (15).
<table>
<thead>
<tr>
<th>Years’ Classroom Experience</th>
<th>Average CECT score</th>
<th>Average number of alternative conceptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>less than 10 (K, C)</td>
<td>29.0</td>
<td>14.0</td>
</tr>
<tr>
<td>10 (F, G, H, I, M)</td>
<td>39.8</td>
<td>11.2</td>
</tr>
<tr>
<td>more than 10 (A, B, D, E, J, L)</td>
<td>42.8</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Table 11. Years of experience teaching advanced chemistry, number of alternative conceptions maintained, and scores on the CECT.

4.4. Descriptions of Equilibrium – Language Used

The second research question in this study concerned how teachers explained the concepts of equilibrium, specifically, whether they were describing these concepts in terms of reaction rates, equilibrium law, or Le Châtelier’s principle. As described earlier, an explanation involving collision theory would generally suggest a more robust understanding of what happens to both the concentrations and rates of reactions when equilibrium is disturbed. Le Châtelier’s principle is not an explanation for these events, but rather, an algorithmic summary that is only used to predict the outcome of the disturbance.

Coding of the interview data for certain words and phrases (See Table 3) allowed for some insight into this area. Language describing the concepts of equilibrium in terms of equilibrium law and reaction quotients was observed least often in the interview data. This is not surprising, since there were no mathematical questions in the interview, nor were there any conceptual questions regarding what would happen given initial concentrations of reactants and products. However, the teachers used the equilibrium law (sometimes along with a mention of collisions) to show how concentrations would change to maintain an equilibrium constant when a disturbance to equilibrium occurred:

SG: Okay. And, why would a temperature change...K, but not increasing something, let's say, something else that would reverse the reaction, like adding more NO₂?
A: Because when you add NO₂, you're going to have more collisions of the NO₂, which is going to increase, then, the concentration of NO and O₂. So, let's say you have, let's say you have, initially, two squared over two squared times 1. Okay? And that’s—that’s at equilibrium. And now you change, and you make it 2.4. Okay? [SG: Mmm-hmm.] So, what’s going to happen is, that... this is going to increase, because you're going to produce more products. This is going to increase, and this is going to decrease, until the ratio, raised to the powers of the coefficients, are still going to equal the same thing, because you haven't favored the reverse reaction over the forward reaction for equilibrium.

E: Equilibrium constant only changes with temperature.
SG: Why?
E: ...This is just messing with concentrations, so it's always gonna come back to that ratio.
These mathematical explanations did not provide evidence of a conceptual understanding of what was occurring at the sub-microscopic level.

What seems most discernible from the data totals is that teachers generally tended to use the more algorithmic language of Le Châtelier’s principle and the equilibrium law when discussing changes to concentration and used collision theory language when discussing changes in rates. This underscores the separation of these two topics in the chemistry curriculum and gives some evidence for the fact that these teachers, as a whole, generally did not integrate the topics. In addition, the teachers who favored Le Châtelier’s principle explanations tended to utilize mathematical explanations more frequently (e.g., teachers E, F, K, and L). This is not surprising, since the use of both Le Châtelier’s principle and the equilibrium law represent algorithmic ways to explain equilibrium concepts.

Of interest is the comparison of the language used in the responses to the scores on the CECT and the number of alternative conceptions expressed during the interview. Those who answered more of the questions on the CECT correctly were generally those who explained more of the concepts using collision theory. There did not seem to be any relationship between the backgrounds of the teachers and their choice of explanations, although those teachers who maintained the highest number of alternative conceptions tended to utilize Le Châtelier’s principle and mathematical discussions more often. With the exception of teacher C, teachers who expressed more than ten alternative conceptions all used collision theory language less frequently. Table 12 shows the number of instances where language relating to the different types of explanations were used, along with the CECT scores and number of alternative conceptions expressed during the interviews.
<table>
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<tr>
<th></th>
<th>LCP, N(%)</th>
<th>RR/CT, N(%)</th>
<th>EL/RQ, N(%)</th>
<th>CECT</th>
<th>#AC</th>
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<td>A</td>
<td>overall: 3(15.8)</td>
<td>overall: 15(78.9)</td>
<td>overall: 1(5.3)</td>
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<td></td>
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<tr>
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<td>R: 7</td>
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<tr>
<td>B</td>
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<td>overall: 14(93.3)</td>
<td>overall: 0(0.0)</td>
<td>47</td>
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<td>R: 0</td>
<td>R: 8</td>
<td>R: 0</td>
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<td>C</td>
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<tr>
<td>D</td>
<td>overall: 5(33.3)</td>
<td>overall: 10(66.7)</td>
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<td>E</td>
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<td>F</td>
<td>overall: 7(63.6)</td>
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<td>H</td>
<td>overall: 4(40.0)</td>
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<td>I</td>
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<td>J</td>
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<td>K</td>
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<td>M</td>
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</table>

Table 12. Teachers’ use of language descriptors. Number of instances of each type of language used (percent); Le Châtelier’s principle (LCP), reaction rates/collision theory (RR/CT), equilibrium law/reaction quotient (EL/EQ); during discussion of concentration changes (C); during discussion of rate changes (R); CECT=Chemical Equilibrium Concepts Test score; #AC=number of alternative conceptions expressed during the interview.

It is important to note that there may be bias in this data, since the participants were informed at the beginning of the interviews that what was being studied was how they integrated the topics...
of reaction rates and equilibrium. This means that some of the teachers may have attempted to provide explanations based upon collision theory because they thought they were expected to do so, not because that is what they were most likely to do in their classrooms, or how they actually think about these topics.

4.5. Integration of Equilibrium and Reaction Rates

The final research question addressed the integration of chemical equilibrium and reaction rates in teachers’ curriculum and conceptions. All of the texts used by the teachers in the study have separate chapters on kinetics and chemical equilibrium, and do not have a very thorough treatment of how the topics are integrated. The following sections explore how teachers self-reported the extent to which these topics are integrated in their classrooms, and how interview data could be used to answer this question as well.

**Self-Reported Integration of Topics**

After the questions about predicting, explaining and graphing the changes to concentration and reaction rates when an equilibrium system was disturbed, teachers were asked questions about how they presented the topics in class. Teachers were asked in which order they taught the topics, whether they specifically taught equilibrium in terms of reaction rates, and if they required their students to be able to explain equilibrium concepts in this way. They were also asked about the use of Le Châtelier’s principle, and its place in their curriculum.

Four teachers (30.8%) reported that the integration of topics was prevalent in their lessons. Teacher A did not mention Le Châtelier’s principle at any time during the questioning about changes to the equilibrium system. When asked about this, she clearly thought that discussing these changes using collision theory was much better for a true understanding of equilibrium:

SG: ...One thing that I didn't hear you say, which I thought was kind of interesting...You left out any mention of Le Châtelier. Why did you do that?
A: Well, we're talking about Le Châtelier’s principle, but it's based on collisions. To really understand- Le Châtelier’s principle is taught in Regents chemistry as, ‘A stress to the system goes to the opposite of the stress.’ [SG: Right.] But that's a memorization. And it's not explaining in terms of collisions. When you explain in terms of collisions, then it makes a lot more sense.

Teacher B made similar statements to A.

Teacher G said that although kinetics is covered before equilibrium, collision theory is used throughout the unit on equilibrium:

G: ...In AP Chemistry, because of...the emphasis on the particulate views, we use collision theory throughout the equilibrium unit.

However, he admitted that the discussion of reaction rates does not go very deeply beyond particulate diagrams, and that he does not really have a robust understanding of how equilibrium shifts can be explained by reaction rates:
G: To be honest, we don’t – we don't go that deep. They obviously need to know the shifts and understand what’s happening...at the molecular level. But...they never ask. And, and we- I haven’t gone that deep into- You know, you reach a point where, you know, how far do you go? They don't really pick up, I guess they don't pick up on the...weirdness that happens. But, uh...They’re just basically being trained in terms of, okay, what is happening to the rates as you increase temperature, decrease temperature, and so on. What’s happening in terms of shifts. But that was what I had gotten when I did the online portion, where I started looking at it and saying, ‘Wow, I don't really know what’s going on at this level myself.’...But, no, we don't go this far.

Teacher K also reported integration of the topics in his classroom, though not “as elaborately” as the discussion during the interview. He stated that a response by his students using Le Châtelier’s principle would not be sufficient, and that he would probe the students a bit more.

The other nine teachers (69.2%) taught equilibrium and rates as separate topics and did not expect their students to explain shifting equilibrium reactions in terms of reaction rates. Teacher C spoke about requiring students to decide whether a question is an “equilibrium question” or a “kinetics question,” suggesting that if a question is an equilibrium question, then the use of Le Châtelier’s principle would be acceptable to him. Teacher D said that since the IB test did not ask students to integrate the topics, he did not teach or require the students to respond that way. Teachers M and I responded similarly about AP questions:

I: Do I use reaction rates in equilibrium? … I guess the easiest way to say it is 'not often'.
SG: What about Le Châtelier’s Principal? Do you do that with the AP students?
I: All the time.
SG: And do you expect them to be able to explain it?...
I: I have never. Until today, I've never really thought about the way you pose the questions. And, as a result I just teach it so that they can answer AP-like questions. If I see something on an AP, I try to teach so that they have an idea of how to approach and answer those questions.

M: I think it's even enough for the AP, because they'll accept an answer such as, 'if the left- hand- if the reactant side experiences a stress of any sort, there's going to be a shift to the right.' And then you can just apply it to anything that's going on. There's no further explanation needed.

Teacher E, after stating that the topics are separated in his class as well, suggested that it was a lack of time that keeps the discussions about integration from occurring:

E: ... not to the extent like it really could go. Usually, the sad thing is, it’s at the end of the year, and I'm racing to get stuff done and therefore [laughs] therefore, you know, the in-depth discussion is very limited to just like the textbook questions.
He also said that most of the explanations of Le Châtelier’s principle are done using calculations. Teacher L shared that approach.

Teacher H echoed the feelings of teachers D and E. After stating that she did not integrate the two topics for fear of confusing her students, she explained:

**H:** Yeah. Yeah. I mean, it's more of the shifting, and I definitely don't get into the rates and that too much.

**SG:** Is there a particular reason why?

**H:** I've just not seen enough questions like that to warrant me getting too much into it, and I've got limited time.

Teacher J plainly stated that she did not integrate topics:

**SG:** …When you teach equilibrium, do you teach it in terms of reaction rate?...

**J:** No. I just do pretty much a quick mention that equilibrium is based on the reaction rate. But no ... we don't talk about rate all, I think, with equilibrium.

Then, she elaborated as to why this was the case:

**J:** ...with AP, there's just so much quantity...And especially since we start in September, and I feel like we're already a month behind...We're really moving pretty quickly, and there's never been any mention of rate with equilibrium. So I don't really focus on it from that point. The way that the AP exam usually talks about Le Châtelier, they'll ask them, you know, ‘what will happen?’ And ask them to explain it based on Q. What direction is the shift going to be. But I've never seen a question where they asked them about rate. And so, I guess that's why I've never really thought about it from the rate point of view.

Teachers F and I realized from the interview that the topics should be integrated more in their lessons:

**SG:** When you teach it, do you at all talk about them together like this?

**F:** No. You've changed my perspective on how I'm presenting it...It [referring to the CECT] made me think, and I realized I was missing something.

**SG:** …When you work with Le Châtelier’s principle, do you teach it just from the standpoint of, 'if you do this then this will happen. If you do this, this will happen’?

**F:** Yes.

**SG:** So you do not require them to sort of explain why Le Châtelier’s principle works at all?

**F:** I haven't, but I will...Again, this is really- [**SG:** It's new, right?] This really has introduced a better way to approach it...If I'm struggling, it just compounds it for the students.

**I:** …I guess I would want them to know the end result, and...I'm gonna change. Next year, I'm gonna...do it to your way. I've never broken it down that way. So, I have always done it, 'What will happen to the products?' and 'Why?' And, you
know, in terms of stresses and whatnot. Um, but I've never asked them to draw the graphs.

The lack of integration of topics is somewhat evident in the number of alternative conceptions maintained by the teachers. The average number of alternative conceptions held by those teachers who integrated the topics was 8.0. The average number of alternative conceptions held by those teachers who did not integrate the topics was 10.4. The average CECT scores for integrating teachers and non-integrating teachers was 42 and 38, respectively.

**Evidence of Integration of Topics from Interview Questions**

Besides asking teachers to report whether they integrated the topics of reaction rates and equilibrium, evidence of the integration or non-integration of these topics was extracted from the interview data. Whenever a teacher clearly and naturally used collision language to express changes to the equilibrium condition, this was evidence that the two topics were integrated in their minds. For example, when discussing the mixing of reactants and the approach to equilibrium, teacher A clearly integrated the topics:

A: Predict what's going to happen the concentrations as you approach equilibrium.
SG: Yes.
A: So NO₂ is going to increase, and NO and O₂ are going to decrease.
SG: Okay. And why do you think so?
A: As you approach equilibrium...initially, you only have reactants. So initially, there's going to be much more of a drive to produce products, since there are no products that can combine with each other to produce reactants. So, initially, it's going to go forward very much. As you build up the concentration of NO₂, there are going to be more collisions between NO₂ and itself, so it can do the back reaction, until the rate of the reverse reaction is going to increase, and eventually the rate of the reverse reaction's going to equal the rate of the forward reaction. The concentrations of each of the components is going to be constant.

Teacher A also talked about rates when asked for the concentration change when addition NO was added to the system at equilibrium, demonstrating how the two topics were weaved together in her mind:

SG: …predict what will happen to the concentrations of NO, O₂, and NO₂, if I suddenly add more NO.
A: Nitrous oxide. So, your adding more NO, so there's going to be more collisions between NO and O₂ because you have more reactants. So, the rate of the forward reaction's going to increase.
SG: Let's worry about rates a little bit later. We'll talk just about concentrations here. What happens to the concentrations?
A: So, what happens is that you are increasing concentration of NO. So, there's going to be more collisions between NO and the remaining O₂. And so, the O₂'s going to go down. And this NO₂'s gonna go up. 'Cause you're gonna produce more product.
Teacher B similarly responded:

   **B:** Okay. So, you're increasing NO, so the rate of the forward reaction will go up. That will cause some - that will cause consumption of some of the added NO, it'll cause consumption of the O₂, so the O₂ concentration will be less than what I have here. The NO will have jumped up and then go back down, but not to there [referring to the original equilibrium line]. And the NO₂ will increase.

Other teachers simply ignored the relationship between rate and equilibrium, or even suggested that they be treated separately. For example, when asked what would happen to the forward and reverse reaction rates when additional NO was added to the equilibrium system, teacher M responded:

   **M:** Well, that's going to never change, if the temperature doesn't change.
   **SG:** And so, what would that look like on the graph?
   **M:** The rate, here? [SG: Mmm-hmm.] Okay. So, this is a Le Châtelier’s shift, but it's only in terms of concentration. So, there'll be no change in the rate.

When probed further, the separation between the two concepts becomes even more apparent:

   **M:** …You didn't disturb the temperature. All you did was change a concentration. So, nothing's going to change the temperature.
   **SG:** ...Without changing the rate, how do you get the shift?
   **M:** Well, the shift is only in relative quantities. So, the quantity shifted has nothing to do with the rate. I know that it's spoken of as a temporary increase in the rate of the forward, but I don't really like that term, because if you talk about rates changing then you're really implicating a temperature change. [laughs] So, as far as my students go, I tell them to never touch the rate unless the temperature changes.

**Summary**

Most teachers in the study did not integrate the topics of chemical equilibrium and reaction rates for a variety of reasons, including lack of time, lack of emphasis by the AP and IB exams, and lack of robust understanding on the teachers’ part. Many agreed, however, that the integration of the topics was important, interesting, and required for a deep conceptual understanding.

**4.6. CECT and Interview Data Convergence**

Interview data corresponded well with the CECT data, providing evidence for validity and reliability of the data sources. Answers to each question on the CECT were matched with interview data for convergent validation. If a participant got the question wrong on the CECT and provided that same incorrect information during the interview, that was coded as a matching response, as was correct CECT answers with correct answers during the interview. If a concept tested on the CECT did not come up during the interview, it was not included in the tabulation.
Table 13 shows the number of matching responses and the percent agreement between the interview data and the CECT data for each participant. The average percent agreement was 92.1%.

<table>
<thead>
<tr>
<th>Participant</th>
<th>matches (% agreement)</th>
<th>Participant</th>
<th>matches (% agreement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>44 (95.7)</td>
<td>H</td>
<td>45 (97.8)</td>
</tr>
<tr>
<td>B</td>
<td>46 (100.)</td>
<td>I</td>
<td>43 (93.5)</td>
</tr>
<tr>
<td>C</td>
<td>34 (73.9)</td>
<td>J</td>
<td>46 (100.)</td>
</tr>
<tr>
<td>D</td>
<td>35 (97.2)</td>
<td>K</td>
<td>42 (91.3)</td>
</tr>
<tr>
<td>E</td>
<td>42 (91.3)</td>
<td>L</td>
<td>45 (97.8)</td>
</tr>
<tr>
<td>F</td>
<td>39 (84.8)</td>
<td>M</td>
<td>37 (80.4)</td>
</tr>
<tr>
<td>G</td>
<td>43 (93.5)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 13. Agreement between interview and CECT data sources. Of the 47 questions on the CECT, one was ultimately not directly tied to an interview question. Therefore, the maximum number of matches was 46.

4.7. Conceptual Change

One finding that emerged from the pilot study was how powerful the graphing tasks seemed to be for allowing each of the teachers to reason through each principle. Keeping that in mind, the interviews were structured so that there was an initial response (a prediction of what would happen to the concentrations and rates when the equilibrium was disturbed), an explanation response, and a graphing task. During the graphing task, participants were asked to think aloud as they drew, and explain why they had drawn their graphs in that way. None of the thirteen teachers had seen the graphing tasks before, except for the graphs for the initial approach to equilibrium in terms of concentrations and rates. Common comments such as, “I’ve never really thought about this before” or “I don’t know that I’ve ever drawn this kind of graph before” gave evidence of how unfamiliar this type of activity was to these teachers. The fact that answers changed from the initial response after the graphing task is a good example of how graphing might be used as a powerful tool to affect conceptual change. This task satisfies the initial condition that Posner et al. (1982) described as a requirement for a conceptual change, namely, a person must be dissatisfied with his or her current knowledge. During graphing, there were many examples of how explanations didn’t match what their graph was telling them, and fixing the graph provided a new and fruitful way explain the ideas, which is also part of Posner’s conceptual change requirements. Instances where the graphing tasks caused the participants to either more fully develop or change their explanations to a more correct or robust response were coded as “positive conceptual change.” There were also instances where the graphing tasks created doubt that could not be reconciled, or that caused a participant to change his or her response to one that was less correct. These were coded as “negative conceptual change.” Whether the graphing tasks elicited positive or negative conceptual change, these tasks also showed how, even if teachers’ initial answers to interview questions were correct, the knowledge that they had about the concepts was not as robust as it should be in order to integrate the concepts of reaction rates and equilibrium. It also demonstrated, however, that these teachers
could develop more complete answers upon reflection. The following sections give examples of positive and negative conceptual change in the participants in this study.

**Positive Conceptual Change**

Examples of positive conceptual change were plentiful and could be identified because participants’ answers on the CECT did not match what they finally decided to be the truth after drawing the graphs. One example of positive conceptual change involved a common alternative conception identified on the CECT, held by 9 of the 13 teachers, that when a system was allowed to re-establish equilibrium after additional reactant was added to it the new equilibrium rate would be the same as the equilibrium rate before the additional reactant was added. Upon graphing, however, five of the teachers (56%) ultimately changed their answer to reflect what actually happens:

J: ... [pause, laughs] ... I mean, right now I'm showing it higher...because we have more particles now.

and

A: Now the question that you're gonna ask me is, is this line higher than this line? [referring to the new equilibrium rate line] [SG: I am going to ask you that, yes.] [laughs] Um...The K is going to be the same as long as the, the, um...As long as the temperature is the same, the K is going to be the same. But that's not telling us about the rate. Because you have probably more...molecules in total in the system, you're going to be more collisions...either way, even at equilibrium...So...The rate of the forward is always going to equal the rate of the reverse. But I would say that the line is going to be slightly higher because you have more collisions because you have more molecules.

and

D: So actually, I changed what I initially predicted. [SG: What are you changing?] I'm changing that the new rates don't have to be the same as the initial equilibrium rates.

A more extreme example of this occurring was with teacher G, who initially said that upon addition of NO, the rate of the forward reaction would increase and the reverse reaction would decrease. He then drew a graph where the rates were unequal at the new equilibrium (see Figure 28, solid lines). After discussing the graph, he not only changed it to having the rates equal again (see Figure 28, dashed lines), but also indicated that the new equilibrium rate was higher than it was before. This same conceptual change, regarding equilibrium rates that were not initially drawn equal, happened with teacher F (see Figure 27), however, he maintained that the rates at the new equilibrium would revert to the original rate.

There were also instances of conceptual change that improved a teacher’s understanding, but did not result in a perfect answer, demonstrating how persistent alternative conceptions can be. For example, Teacher L initially said (on both the CECT and the initial line of questioning) that the rate would return to the initial rate, but as she graphed, she reasoned that:
L: So, the idea is, because...I made more NO$_2$...I would say that the reverse reaction has got to increase a little, too.

However, L after determining that the rates will increase, she returns to the idea that, in the end, the rates will revert to their original equilibrium:

L: I made it the same just because I haven't changed the temperature... um...[pause]...And the K is still the same.

Even the act of answering the questions on the CECT elicited a deeper thought process. Teacher B answered the question correctly on the CECT, but commented that:

B: I thought that was an interesting question. When I - That was on your thing last week [referring to CECT] and I thought, I never - I don't normally talk about that. But I believe the rate will be slightly higher than it was before.

In all, for this question, graphing affected conceptual change in 5 of the nine teachers who initially answered incorrectly and caused partial conceptual change in 2 other teachers. Therefore, for this question, graphing positively affected 78% of the participants.

**Negative Conceptual Change**

An example of negative conceptual change would be demonstrated by teacher E, who initially said that, upon a decrease in volume, the rate of the forward reaction would increase, and the rate of the reverse would start to increase until the final equilibrium rate would be higher than the initial equilibrium rate, but then changed his mind:

SG: And the final equilibrium position?
E: Will be...the rates will be slightly higher than where it was started.
SG: And why would that be?
E: ...[long pause] Actually, taking that back. Some strange reason. I think the change in pressure causes the reactant...I'm gonna change this...The reverse is actually going to be decreased initially. And the forward’s going to be increased initially. And it's going to come right back to the same rate.
SG: So, this is- this is equal to where it was before? [referring to new equilibrium line]
E: Yes.

**Summary**

Similar instances of positive and negative conceptual change were observed in the other questions. **Table 14** shows the number of instances of conceptual change by participant. Although there were examples of both types of conceptual change, the instances of positive conceptual change were much more common. Of the 34 instances of conceptual change observed among the 13 participants, 28 (82.4%) were positive and 6 (17.6%) were negative.
<table>
<thead>
<tr>
<th>Participant</th>
<th>Instances of positive conceptual change</th>
<th>Instances of negative conceptual change</th>
<th>total instances of conceptual change</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>4</td>
<td>0</td>
<td>4</td>
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<td>B</td>
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</tr>
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<td>C</td>
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<tr>
<td>D</td>
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<tr>
<td>F</td>
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<td><strong>28</strong></td>
<td><strong>6</strong></td>
<td><strong>34</strong></td>
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</table>

Table 14. Instances of conceptual change in the thirteen teacher participants in this study.

4.8. Summary

Through the administration of the online CECT and the in-person interviews, the research questions were answered. The alternative conceptions maintained by these teachers were uncovered, their use of reaction rates to describe changes to reactions at equilibrium were categorized, and the integration of the topics of equilibrium and reaction rates was explored. In addition, the graphing tasks posed during the interview were shown in some cases to affect conceptual change. The following chapter discusses the implications of the research and its major findings, and recommendations for education and policy changes.
Chapter 5
Discussion

5. Overview

This research was conducted in response to a call by researchers for more studies about teachers’ subject matter knowledge, and how the alternative conceptions they maintain, affect teaching and learning (Cheung, 2009a, 2009b; Kruse & Roehrig, 2005; Talanquer, et al., 2009). This study sought to fill a gap in this area of research, concerning equilibrium and reaction rates. It adds to the body of knowledge that exists for improving the development of teacher education programs, and may be used to inform certification requirements, professional development programs, textbook development decisions, classroom practices, the development of advanced chemistry curricula and exams, and state policies. This study was novel in that it focused on experienced high school teachers of advanced chemistry, a population for which little prior research has been reported. It also included graphing tasks, relating reaction rates to equilibrium, that have not previously been used to probe the conceptual understanding of teachers. The study demonstrated the power of the graphing tasks in eliciting alternative conceptions held by the teachers. It is intended that the findings of this study might function as a source for rich discussions and in-service workshops concerning this area of chemistry teaching. Major findings of this study include:

1. Forty-seven alternative conceptions, expressed in almost 150 instances, were held by the teachers in this study. Though these alternative conceptions have been reported in the literature, this finding was unusual in that it identifies alternative conceptions within a group of advanced high school chemistry teachers with an average of 11.4 years’ experience teaching advanced high school chemistry. This demonstrates that the alternative conceptions commonly found in the literature, held by students and teachers with little or no teaching experience, remain throughout teachers’ careers. Alternative conceptions regarding reaction rates were the most common.

2. These experienced teachers generally had difficulty integrating the concepts of chemical equilibrium and reaction rates, and they were generally unable to explain the concepts of equilibrium using the concept of rates of reactions.

3. When the teachers in the study explained the concepts of chemical equilibrium, they often could not successfully incorporate these ideas into concentration and rate graphing tasks, which demonstrated a shallower understanding about these concepts than was expected.

4. The alternative conceptions expressed, and the ability of teachers to integrate chemical equilibrium with reaction rates, was less related to the educational
backgrounds of the participants, and more related to (a) the number of years teaching experience and notably (b) whether they held primary certifications in chemistry.

5. The language used to describe chemical equilibrium was divided between the use of Le Châtelier’s principle, equilibrium law, the reaction quotient, and collision theory and reaction rates, based upon what was being described. Le Châtelier’s principle along with equilibrium law and reaction quotient language was most often used to describe changes in concentration, whereas collision theory language was used to describe changes in rates. Those teachers who scored better on the Chemical Equilibrium Concepts Test (CECT) and expressed fewer alternative conceptions generally used the language of collision theory more often.

6. These teachers self-reported, and the interview data suggest, that they generally do not integrate the concepts of chemical equilibrium and reaction rates into their classrooms for reasons such as (a) a lack of time and (b) the fact that their final assessments do not require students to integrate the topics.

7. The CECT was an effective measure of teachers’ understanding of these topics, and was supported by the interview data.

8. The graphing tasks employed during the interviews promoted reflection and conceptual change, though there were instances of both positive and negative conceptual change.

The following sections discuss the implications of this research in the areas of teacher knowledge and subject matter structure (section 5.1), implications for textbook and curricula development (section 5.2), implications for teacher preparation programs, and certification (section 5.3), recommendations for professional development opportunities (section 5.4), and recommendations for classroom practice (section 5.5). The assumptions and limitations of the study are also discussed (section 5.6).

5.1. Teacher Knowledge and Subject Matter Structure

This research study underscored some of the relevant findings found in previous studies that looked at in-service teachers and their chemistry knowledge. The best parallel to a previous study was to that of Kruse and Roehrig (2005), who summarized that teachers do not often get to the chance to challenge their own conceptions in chemistry, and thus do not even realize that they maintain alternative conceptions, have gaps in their knowledge, or that important links between topics are missing from their knowledge base. These ideas were evident in the current study, as teachers remarked quite often throughout the interviews that they had never thought in depth about this topic in the way that the questions and tasks were requiring, or that they simply did not know the answers to the questions. Kruse and Roehrig also found a link between those teaching out of their certification areas and the prevalence of alternative conceptions. The current study expands on that finding. Though all of the teachers in the current study held chemistry certification, those who held chemistry certification as their secondary certification expressed more alternative conceptions than those whose primary (or only) certification was in chemistry.
The conceptual framework for this study was built around the idea of teachers’ subject matter structure (Gess-Newsome & Lederman, 1995; Lederman, Gess-Newsome, & Latz, 1994), which is defined as how teachers understand and integrate the concepts they teach. Contributing to a teachers’ subject matter structure for equilibrium and reaction rates is (a) a solid subject matter knowledge, (b) knowledge of the different levels of representation, (c) knowledge of the curriculum, (d) the teacher’s own beliefs about efficacy and the importance of integrating topics, (e) how concepts are presented in the textbook, (f) the experience of the teacher, and (g) the teacher’s own alternative conceptions about the topics.

This study uncovered deficiencies in some of these factors, which ultimately translate to poorer subject matter structure for these teachers. Taking these factors one at a time, the subject matter structure of these teachers can be generalized: (a) The teachers generally had a less than strong general subject matter knowledge in this area, scoring an average of 39.5 out of 47 (84%) on the CECT assessment, which agreed with their answers to interview questions; (b) on the whole, the teachers had a good command of the different levels of representation, as they were adept at switching between particle diagrams, chemical equations, and macroscopic properties of matter; (c) the teachers had a general sense of the curriculum, suggesting that the reason they did not intentionally integrate the topics is that the questions on the final assessment exams (AP/IB) are not presented in this way; (d) Teachers tended to make comments about efficacy and beliefs when they suggested that they “teach to the test”, or that it would be too confusing for their students to put the topics together; (e) The teachers generally followed their textbook which, in all cases, separate the topics of chemical equilibrium and reaction rates. However, the fact that not one of the teachers suggested that the product under review in this study (NO₂) would dimerize in an equilibrium reaction to form N₂O₄, though this was a featured reaction in all of the textbooks used by the participants, suggested the possibility that they had not re-read their text in some time. This might be a negative consequence of (f) the fact that these teachers collectively had an average of more than 11 years teaching advanced chemistry; (g) Though the teacher participants in this study had quite a bit of experience, they maintained a total of 47 different alternative conceptions expressed in almost 150 instances, ranging in topics such as the meaning of the equilibrium constant, the existence of a stoichiometric ratio between reactants and products at equilibrium, the dynamic nature of equilibrium, and the relative rates of the forward and reverse reactions as equilibrium is re-established after a disturbance. Taken together, this suggests an inadequate subject matter structure, which may explain why the teachers had so much difficulty with the questions and graphing tasks contained in the interviews.

A main finding of this study about subject matter knowledge and subject matter structure was that experienced teachers of advanced chemistry often relied on simpler algorithms, such as Le Châtelier’s principle, as the basis for their explanations of chemical equilibrium, and that they did not tend to integrate the topics of equilibrium and reaction rates. Though this study focused on equilibrium and reaction rates, it would be reasonable to assume that a similar lack of depth in understanding might be found when focusing on other topics in chemistry. Additionally, the lack of integration was uncovered only during thorough probing and graphing tasks, which teachers do not often get the opportunity to experience. We assume that, upon securing their certification, teachers have complete understanding and integration of the material they teach, but this study revealed that this does not appear to be the case. In addition to uncovering a lack of depth of knowledge, the graphing tasks appeared to promote conceptual change, and provided a source of much needed reflection for the teachers. Depth of knowledge is important for a teacher to be fully effective in teaching advanced chemistry, as a teacher’s subject matter structure will affect
the development of their PCK, and the instructional choices they make in their classrooms. Simply put, knowledge cannot be transformed if it is not well-understood. The graphing task could also be incorporated into teachers’ lessons, as a means of seeing whether students have a grasp of the interconnectedness of these topics.

Based on the results of this study, the components of subject matter structure could also be expanded to include a teacher’s primary certification, since those teaching with primary certifications outside chemistry had more alternative conceptions, had lower scores on the CECT, and had more difficulty with the graphing tasks, suggesting a lack of topic integration. Also, subject matter structure might include a component that describes a teacher’s interest in and openness to challenging their own conceptions, since this contributes to their overall conceptions of a topic. Exposure to educational research might allow teachers to more thoroughly understand the relationships between topics and give them the opportunity to reflect on their own knowledge. The one thread that bound all of the teachers in the current study was their willingness to learn something new, and their general lack of defensiveness or embarrassment upon the realization of their alternative conceptions. These teachers were eager to discuss the “correct” answers after the interviews, and some even mentioned that they would consider changing the way that they taught the subject. One of the teachers in the pilot study sent an email asking for a written description of what we had discussed. Though it seems to be the nature of those willing to participate in a study such as this, this researcher is hopefully optimistic that most teachers would be interested in challenging and developing their subject matter knowledge if the opportunity presented itself, in such forms as a better-organized and integrated textbook, a more integrated curriculum for advanced courses, more complete teacher preparation program experiences, certification requirements that are more stringent with respect to content knowledge, and appropriate advanced professional development opportunities. These are all discussed in the following sections.

5.2. Implications for Textbook and Curricula Development

In most advanced chemistry classrooms, textbooks and published curricula inform classroom teaching. This is true for both novice teachers looking for a place to begin to develop their course lectures and activities, and for the experienced teacher aligning his or her course to the school calendar or to outside assessments. These are also the primary sources of information for teachers who have been out of school for many years (as is the case with experienced teachers) or who are teaching outside of their areas of expertise. Thus, it is important that textbooks and curricula contain and demand the deep, integrated conceptual knowledge that is so important for developing a complete understanding of chemical concepts.

Textbook Development

A recommendation from this study is that the authors of advanced chemistry textbooks address, in more detail throughout the chapter, the dependence of equilibrium on reaction rates, so that students and teachers can fully appreciate the integration of these topics. An understanding of equilibrium is not complete without this. It is not sufficient to expect students and teachers to make those connections themselves simply by defining equilibrium as a condition where the forward and reverse reaction rates are equal. Rate graphs, presented alongside concentration graphs, could be shown to demonstrate not only how a system reaches chemical equilibrium, but how rates and concentrations change when equilibrium re-establishes
after a stress. Questions and exercises could be provided to allow teachers to determine whether students have a firm grasp on this integration. Le Châtelier’s principle, although a handy mnemonic device worth discussion, is often misrepresented in texts, and should not be the only rationalization for changes to an equilibrium system. Instead, it may be treated as a summary of chemical knowledge that students gain while discussing rates or reaction. Textbook developers might consult Green and Damji’s online textbook for the IB program, which specifically argues that Le Châtelier’s principle is just a “memory aid,” and that the reasons for the shifts in equilibrium position relied on what happened to the rates of reaction when a condition was changed (Green & Damji, 2007).

Alternatively, and perhaps a more effective improvement, would be the creation of a separate chapter after the equilibrium chapter, but before the applications of equilibrium chapter, that looks at equilibrium systems from the standpoint of reaction rates. This would be an excellent way to make the interrelationship clear to both teachers and students. It could be in this chapter that the concepts covered in Le Châtelier’s principle could be more fully treated. A discussion of each change to a system at equilibrium and how both rates and concentrations are affected, complemented with mathematical explanations and graphs, would be optimal. This researcher understands that advanced chemistry textbooks are already long (most exceed 1000 pages), and that space within the pages is in short supply. However, significant space dedicated to a more robust explanation of subject matter would not be wasteful to those trying to master the subject, which demands an understanding of how the topics are related.

**Curricula Development**

As with textbooks, it is important to delineate a curriculum for our chemistry students that promotes a deep conceptual and integrated understanding of chemical topics as opposed to presenting topics independently from each other. For example, there is usually no indication early in a course that many chemical reactions are reversible. A focus on stoichiometry, limiting reactants, and percent yield early in the curriculum may lead students to come to the alternative conception that all reactions will proceed to completion. Later in the curriculum, when chemical equilibrium is introduced, confusion is bound to be a product of those conceptions. Deep conceptual understanding of chemistry requires the expectation that students understand the connections between the various topics in the curriculum, such as between reaction rates and chemical equilibrium. The Advanced Placement course outline, which is followed by most of the teachers in this study, does not specifically suggest the need for the integration of topics (The College Board, 2014). When examining the “Part II” questions on these exams, which are short answer, explanations, and calculations, it is observed that different parts of each question often include material from different chapters. However, there have not been any examples of the tasks (such as the graphing task presented to the teachers) that require knowledge of more than one topic at the same time. The College Board, which develops the AP exam and releases material to help teachers prepare their classes did publish a guide to the equilibrium unit that included the integration of equilibrium and rates of reaction, however, none of the teachers in the study had seen it. Since knowledge of curriculum is part of the subject matter structure that teachers use to decide what and how to teach in their classrooms, curricula such as that of Advanced Placement Chemistry might be advised to move away from rote use of Le Châtelier’s principle to explain changes to the equilibrium condition, a focus on its connection to reaction rates.

When discussing the AP chemistry course with teachers, most of them spoke about the time management aspect of delivering the AP course to their students. They mentioned that there
is simply not enough time in the year to cover all the topics required of the AP curriculum and still integrate topics for a more robust overall understanding of chemical concepts. It is important to note that, while AP courses for other disciplines cover the material found in a one-semester college course, AP chemistry covers the material for a two-semester college course. For high schools that begin classes in September and administer the AP exam in the beginning of May, this translates to an academic year that is short, approximately 150 days. The result is a very fast-paced course with too high a conceptual density (Rowe, 1983) to be effective at promoting integrated understandings. The way advanced chemistry is presented in the United States is quite different from how it is presented in other countries around the world, which generally teach chemistry over multiple years or integrated with other sciences over many years. In American high schools, there are also various structures in which the AP chemistry course is delivered. Different schools have various time allotments for the course (e.g., single periods, double periods, alternating single and double periods, block scheduling, etc.) and/or different requirements for entrance (i.e., teacher recommendation, student self-selecting, etc.). In addition, some schools offer AP chemistry as a first chemistry course, while others offer it only after an introductory course in chemistry. This results in a non-uniform advanced chemistry experience for students.

There has been effort on the part of the College Board to amend the curriculum, and to reduce the number of topics covered in the chemistry AP course so that teachers can focus on providing a fuller, more interconnected experience. Rather than creating a new course structure, however, topics were simply removed from the syllabus. Since the College Board recommends an AP course only after the successful completion of a first course in chemistry, the topics removed (e.g., phase diagrams, exceptions to the Aufbau principle) were eliminated because they were considered “prior knowledge” (The College Board, 2014). However, many teachers continue to teach the topics removed because other topics do not make sense without them, especially for those students taking AP chemistry as their first (and only) chemistry course. Removing topics, then, does not solve the problem of the massive amount of material that must be covered in such a short amount of time, and there remains the high probability that teachers will rush to complete the syllabus before the exam in May.

As an alternative, perhaps the AP Chemistry course could be split into two separate courses, as was done with AP Physics B, which has been discontinued and replaced with “AP Physics I” and “AP Physics II”. These courses cover all the topics included in the old AP Physics B curriculum, over two years, and each is equivalent to a one-semester course. According to the College Board,

AP Physics B was split into two separate, full-year courses so teachers now have the time they need to help students develop a deep understanding of foundational physics principles…This helps prepare students for success in future course work in the sciences. The full year also gives teachers flexibility to explore some extra topics that align either to their own expertise or to physics content standards as specified by their state (The College Board, 2018).

That extra time in a chemistry curriculum could be spent on the integration of topics as well as extra topics related to chemistry teachers’ interests, such as organic chemistry, biochemistry, or current research within the field. This much better aligns with how chemistry is taught in other countries.
5.3. Implications for Teacher Preparation Programs and Certification

The general goal of policy and practice within chemistry teacher education programs has been to try to help students gain a better grasp of chemical ideas that pose conceptual difficulties. Therefore, much of the research to date has focused on student alternative conceptions within different topics in chemistry. There is often an assumption that chemistry teachers have a firm understanding of all chemical principles and can integrate them well. However, this study revealed that teachers do not have a robust subject matter structure with respect to chemical equilibrium and reaction rates. Chemistry teachers cannot be expected to help their students gain a working knowledge of topics if they themselves do not thoroughly understand them. This research supports Cheung (2009b) that teacher preparation programs need to focus specifically on topics such as these.

One of the more interesting findings for the participants of this study, was the relationship between the number of alternative conceptions expressed by the teachers and the primary certification they held. Those who held primary certifications in chemistry tended to do better on the CECT and on the interview tasks regardless of what undergraduate degree they held. Overall, they expressed fewer alternative conceptions than their counterparts who had secondary certifications in chemistry. It seems logical that this is the result of having more of the foundational chemistry courses that comes from obtaining a primary certification in chemistry. In New York State, a college major in a science (minimally 30 credits) is presently required for certification in that subject. Prior to 2004, science certification required a major in any science, which had to include at least 18 credits (i.e. a minor) in any science named on the certificate, (see Padwa, 2018, p. 7). Teachers must also pass content specialty exam in the science named on the certificate. This means that three teachers in the current study, who held secondary permanent certifications in chemistry were only required to obtain 18 credits in chemistry, which may account for the finding that those with primary certification in chemistry maintained fewer alternative conceptions and scored higher in the CECT. A recent study of chemistry teachers across the United States found that less than 36% of chemistry teachers had a degree in chemistry, and that it was more likely that a chemistry teacher had a degree in biology than in chemistry (Rushton et al., 2014). A study by Padwa showed that, in New York, only 51% of chemistry teachers held primary certification in chemistry, and 32% held biology certification as their primary certification. In addition, 65% of chemistry teachers in New York held more than one certification, with certifications in chemistry and biology being the most common (Padwa, 2018, p. 52). On Long Island, there is an expectation that teachers hold more than one certification in order to be more marketable to schools. This seems counterintuitive, and during the interviews, teachers agreed that it was strange to them that one teacher could hold multiple certifications and teach multiple courses – for example, two teachers that teach both chemistry and Earth science – instead of having teachers hold single certifications and teach within one area of expertise. In New York City, teachers with more than one certification are rare, and teachers usually must have a primary certification in chemistry to teach it. The four teachers in the study who are only certified in chemistry, each expressed how enjoyable it is for them to teach only chemistry, and how they feel comfortable with and knowledgeable in their classes. The average number of expressed alternative conceptions and CECT scores for teachers who (a) hold only a certification in chemistry, (b) hold primary certification in chemistry, and (c) hold secondary certification in chemistry. The results of the study show that having additional
certifications or secondary certification in chemistry does not appear to improve chemistry knowledge. Teachers whose primary certification was not chemistry had not taken any courses in thermodynamics. With regard to teacher preparation, it seems important that teachers return to more foundational, undergraduate courses in chemistry if they are seeking a secondary certification in chemistry. A strong recommendation suggested by this study is that teachers teach what they have initially mastered and leave another area of science to those with mastery in that subject. Though it is recommended by the College Board that only teachers who have a strong chemistry background (e.g., a master’s degree in chemistry) be tasked with teaching AP chemistry, this is not necessarily the practice of all schools. Perhaps this should be a requirement for delivery of the course, and not simply a recommendation.

Teaching certification programs also need to address the sometimes-weak subject matter knowledge and subject matter structure demonstrated by chemistry teachers. It is up to the individual preparation programs, to create and include courses that deal with specific topics within each discipline, to address alternative conceptions found in the literature, and to address the integration of topics. Chemistry-specific methods courses could help to ensure that teachers enter the classroom with robust understandings of the interconnections between topics in the curriculum. It seems that this has not been the experience for the teachers in this study, who reported that they had not taken any course that focused on the concepts of chemical equilibrium. A recommendation inspired by this research, then, would be the creation of a series of courses for aspiring chemistry teachers (as well as aspiring teachers of any science) that specifically focus on the research in the understanding of topics in chemistry, and the alternative conceptions that both teachers and students maintain. De Jong (2005) reflected on the gap between the research and education community, and how research is conducted for the benefit of teachers who are never being exposed to its findings. Teacher preparation coursework, then, should include a study of the research on the various topics that the pre-service teachers will eventually teach. This could be done even in an interdisciplinry classroom consisting of student teachers in the various sciences. Exposing pre-service teachers to the chemical education research literature, and perhaps including more of this work in their subsequent requirements to refresh their certification, would be a promising way for teachers to remain focused on providing their students with a richer experience, since they will have more in-depth knowledge. Since part of a teacher’s success in the classroom is centered on his or her ability to recognize and try and to change students’ alternative conceptions, teachers need to be aware of what those conceptions are as determined by research, and what their own alternative conceptions are. This idea of having pre-service teachers study the research literature on science conceptions can also play a role in the professional development of in-service teachers.

5.4. Recommendations for Professional Development Opportunities

There are many professional development opportunities for the classroom teacher. However, most of these opportunities aim not to improve subject matter knowledge or subject matter structure, but on pedagogy and administrative issues. Although these are important components of classroom teaching, teachers would very much benefit from short courses aimed at deeply studying specific topics in chemistry, so that they can expertly present the information to their students. However, content-based professional development courses in chemistry are rare. These courses might start, similar to Kruse and Roehrig’s study (2005), with a carefully designed concept test to challenge each teacher’s conceptions of the topic. This could then lead to a rich
discussion about common alternative conceptions surrounding the area of chemistry to be explored, and a deep treatment of each concept and how it relates to other concepts in chemistry. Short courses in specific areas of chemistry allow for a thorough treatment and a review of research literature on each topic. This could be done for any topic in chemistry, and teachers would most likely appreciate a refresher course in their subject since, for some experienced teachers, the last time they were in a chemistry classroom as a student was many years ago. Nuances of the subject are lost over time, and the ability to delve deeper into a subject and make connections between topics may be lost. In addition, perhaps some topics were not learned in great detail in those early college years, when students may be less focused on their studies. Also, teachers who teach the same curriculum year after year might forget some of the information they once learned (in their undergraduate college classes) that is not covered in their class. Many teachers attend AP chemistry courses sponsored by the College Board. Some last one or two days, others last up to two weeks. These courses, however, tend to focus more on labs and syllabus than on actual chemistry content. It is assumed that teachers know their subject matter; what is unknown is how completely they know their subject matter. This is where short courses are valuable and worth the time of teachers and the money of school districts.

5.5. Recommendations for Classroom Practice

A classroom teacher has many different options for how to teach an advanced chemistry class. Lectures, labs, activities, and demonstrations all potentially lead to student understanding. This research has identified two major classroom recommendations that help to ensure that the goal of a robust understanding of chemistry is realized: the integration of topics, and tasks that demonstrate overlap between concepts, such as the graphing tasks used in this study. If this sample of teachers is to be an indication of chemistry teachers’ practices, neither is being done consistently in advanced chemistry classrooms. Classes appear to be taught chapter by chapter, with little integration between them.

Integration of Topics

Without the integration of the topics in chemistry, a course often becomes a series of unconnected, unrelated, and individual concepts, and students will not feel as if anything they learn today will have any bearing on what they will learn tomorrow. This leads to students who ask themselves, “What chapter is this from?” so that they may decide what algorithms to apply to solve the problems posed to them. With so many concepts to master, this can lead to student frustration and anxiety. However, with most chemistry topics, there is more than one way to think through a problem, and the more connected the topics are in a student’s mind, the more likely they will find a solution that makes sense to them. Models of bonding can be integrated with acid-base models, for example, to discuss what models are and how they are applied. The use of particle diagrams can be used throughout the curriculum, not just within the bonding and stoichiometry units. A major hindrance to the understanding of chemical equilibrium is that it is taught after the stoichiometry unit, usually in the second half of the year. Thus, students come to assume that all reactions proceed to completion, and are confused when suddenly, all the math and the calculations they so carefully learned and mastered in the first half of the year no longer applies to these “new” equilibrium reactions. Stoichiometry and equilibrium are not separate topics, and should not be presented as if they are.
**Graphing Tasks**

A very effective method for testing the conceptions of teachers and students was found in the interview graphing tasks. As described by White and Gunstone (1992), tasks such as these are crucial for identifying alternative conceptions and facilitating conceptual change. The use of graphing in equilibrium and kinetics was suggested by Wheeler and Kass (1978) to better allow students to overcome alternative conceptions in these areas. More recent reviews by Kozma (2003) and Ainsworth (2008) underscore the benefits of graphing in the development of deeper conceptual understandings, the former including the use of graphing in the study of chemical equilibrium.

The teachers in this study were surprised at how difficult the graphing task was for them, and how adept it was in helping to identify gaps in their knowledge. All of the teachers remained after the interviews to review accurate versions of the graphs and discuss what was lacking in their answers. Each teacher recognized how an understanding of the rate graphs explained much of what they teach algorithmically in their classes. A few suggested that they would include the graphs in their lessons. In a classroom setting, the graphs are an efficient way to create discussion, argumentation, and explanation among students. Students can be asked to draw and explain/defend their own graphs or work together to create one class graph. The ensuing discussion about what would be the “correct” way to draw it creates the integration between topics, higher-level thinking skills, and reflection that we so badly want our students to demonstrate.

**5.6. Assumptions and Limitations of the Study**

This research began with certain assumptions supported by the literature, which affected how the data were obtained and the lens through which the data was analyzed. First, the ability of a teacher to identify and address student alternative conceptions is based on his or her own content knowledge (Piquette & Heikkinen, 2005). Second, teachers have been found to maintain the same alternative conceptions as students with respect to chemical equilibrium and reaction rates (Banerjee, 1991). Last, an assumption was made that teachers choose how to teach chemical equilibrium based upon their own conceptions and subject matter structure (Lederman, et al., 1994).

As with any qualitative study, there are inherent limitations with respect to analyzing its findings. First, analysis of the data obtained from a case study lack generalizability, since the number of participants was low. In addition, the group of participants was quite homogeneous in that they all taught in the same geographical region (Long Island, NY), an area with predominantly low and average need schools. The topic under discussion was a small part of the overall curriculum that they taught. Though not necessarily generalizable to a wider group of teachers, purposeful sampling was used to gain detailed insight into these 13 cases, to maximize the information uncovered. A second limitation of the case study deals with the difficulty of separating researcher bias from the analysis of results. As a chemistry teacher who teaches equilibrium in terms reaction rates, and who dislikes the use of Le Châtelier’s principle as the sole explanation for equilibrium discussions, I am particularly interested in alternative conceptions in these areas and to the lack of integration of these topics in the curriculum. Therefore, I would tend to look at the data through that lens.

Brink (1993) offered four threats to the validity and reliability of a qualitative research study: the researcher, the participants, the social context of the study, and the methods of data collection.
and analysis. To help counteract the effect of the researcher on the responses of the participants, some time was spent informally talking with each participant before the interview began in order to create comfort and gain trust, so that answers to interview questions would be more forthcoming and honest. It is hard for a teacher to admit when he or she simply has never thought about an idea rigorously, and comments such as these during the interviews suggested a high level of comfort with the researcher. Making the subject of the interviews clear to the participants helped to counteract any participant or social context threats to validity. Last, the CECT was used to triangulate the results in order to provide reliability evidence with respect to data collection and analysis.

5.7. Summary and Conclusion

Teaching is a unique profession. Qualities that lead to success in most other jobs – knowledge, preparation, motivation to succeed, enthusiasm, and hard work – do not necessarily guarantee success in a classroom. Although a teacher would fail without the above qualities, the true effectiveness of a teacher is defined by whether or not their students understand the concepts presented to them. Students enter a high school classroom with conceptions they have developed over many years, and it is the teacher’s job to assist them with adopting more scientific conceptions. To that end, a teacher must have strong subject matter knowledge and structure, a reflective nature, and a genuine desire to change the way their students look at the world. Chemistry teachers have a particularly challenging job because the concepts in chemistry are often abstract, complex, and difficult to visualize by students. Furthermore, if teachers have any gaps in their knowledge, or if they maintain alternative conceptions about their subject, these may be passed on to students (Cheung, 2009a, 2009b, Kolomoç & Tekin, 2011; Taber & Tan, 2011) or lead to different instructional strategy choices, development of PCK, and assessment development (Boo, 2005; Kwen, 2005; Talenquer et al., 2009).

This study set out to address three research questions. Research Question 1 sought to identify alternative conceptions held by experienced chemistry teachers about chemical equilibrium and reaction rates, determine how common they were, and whether there was any relationship between those alternative conceptions and the certification and teaching backgrounds for these teachers. It was determined that the thirteen teachers participating in this study did hold alternative conceptions regarding chemical equilibrium and reaction rates, and that the interviews, graphing tasks, and CECT assessment were able to uncover them. As in Hackling and Garnett’s study (1985), these teachers expressed alternative conceptions in every area of chemical equilibrium including the approach to equilibrium, the equilibrium condition, changes to the equilibrium condition, and the addition of a catalyst. Alternative conceptions regarding the ideas of reaction rates were more common, especially when applying them to the concepts of changing equilibrium conditions. Most previous studies have identified alternative conceptions held by pre-service or novice teachers. This study was unique in that it demonstrated (a) how steadfast alternative conceptions can be, and that (b) though the number of alternative conceptions generally diminishes with experience, they are not eliminated altogether. Work done by Nixon & Luft (2015), who studied the sophistication of teachers’ responses to chemistry questions based upon the degrees held by the teachers and their number of years’ experience, showed that those teachers holding degrees in chemistry (as opposed to biology) gave clearer, more complex answers. This study found that a potentially important indicator of alternative conceptions was the primary certification held by teachers. Since, in New York, primary
certification in chemistry requires a degree in chemistry, this research generally supports the work done by Nixon & Luft (2015).

**Research Question 2** asked how teachers of advanced chemistry use the concepts of reaction rates to describe different aspects of chemical equilibrium (the approach to equilibrium, the characteristics of equilibrium, changes to the equilibrium condition) on a submicroscopic level, and if there was any relationship between their educational and teaching background and their ability to describe equilibrium concepts in terms of rates of forward and reverse reactions. A related question, **Research Question 3**, sought to determine whether teachers integrate the topics of chemical equilibrium and reaction rates both in their conceptions and in their classrooms, whether the ability to integrate the topics was related to their alternative conceptions about these subjects, and how integration was related to their teaching and educational background. This research demonstrated that, for these teachers, an understanding of the concepts of reaction rates as they apply to chemical equilibrium were not well understood, which is a hindrance to these teachers being able to integrate the two concepts. Integration was not something that these teachers did naturally, as they (a) had a great deal of difficulty describing changes to an equilibrium in terms other than the language of Le Châtelier’s principle, and (b) were generally unable to draw accurate concentration and rate graphs for changes to reactions at equilibrium. However, for these teachers, the graphing task was determined to be a source of reflection about the way equilibrium and reaction rates are related. The graphing tasks were able to uncover alternative conceptions that would not have been otherwise. In some cases, the graphing task promoted conceptual change, though not all the conceptual change resulted in accepted scientific explanations of the concepts. This was an exciting part of the findings of this study, powerful like that of Cheung’s think-aloud protocol (2009a, b) for solving equilibrium problems where Le Châtelier’s principle does not apply.

The results of this study have important implications for textbook, curricula, and teacher development programs (both pre-service and in-service). First, a greater focus on the integration of chemistry topics is needed in textbooks and in course curricula if our goal is to have our students develop a deep conceptual understanding of all topics as well as an appreciation for how they fit together to form the “big picture” of chemistry. Advanced chemistry courses, which currently have overwhelming high levels of conceptual density, might need to be broken down into multiple courses in order to fulfill this goal. Second, and of utmost importance, is that teacher training must be modified to include chemistry-specific methods courses that focus on mastering the nuances and interconnectedness of topics in chemistry, as well as a study of the research that has been conducted with respect to the alternative conceptions that both teachers and students maintain about each topic. Not only should this be part of teacher training, but exposure to this type of research would be helpful and welcomed professional development opportunities.

There are several avenues to explore as a follow-up to this study. First, a wealth of information about teachers’ integration of chemistry topics could be provided through an in-classroom study, collecting these data authentically rather than as it is reported by the teachers in hindsight. Secondly, it would be interesting to study the effect of experienced teachers’ alternative conceptions on their pedagogical content knowledge and resulting teaching strategies. Experienced teachers have had time to master their craft – trying different strategies yearly to help their students understand concepts in chemistry. It would be interesting to see what strategies teachers have deemed appropriate for a topic and whether what they have chosen relates to the alternative conceptions they hold about that topic. A third avenue of research
stemming from this study might be to attempt to find a relationship between teachers’ alternative conceptions and the resulting conceptions of their students and on their students’ scores on standardized examinations in chemistry.

Chemistry teachers often have goal to provide their students with a solid understanding of the chemical concepts that they will meet in their everyday interactions with the world, and it is the job of educational researchers to ensure that these teachers have the information necessary to accomplish such a goal.
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### Propositions concerning chemical equilibrium for the reaction \(2\text{NO(g)} + \text{Cl}_2(g) \rightleftharpoons 2\text{NOCl(g)} + \text{heat}\)

<table>
<thead>
<tr>
<th>PROPOSITIONS CONCERNING CHEMICAL EQUILIBRIUM</th>
<th>COMMON MISCONCEPTIONS REGARDING PROPOSITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>APPROACH TO EQUILIBRIUM</strong></td>
<td></td>
</tr>
<tr>
<td>1. The concentration of (a) NOCl increases, (b) NO decreases, and (c) Cl(_2) decreases</td>
<td></td>
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<tr>
<td>2. The rate of the (a) forward reaction decreases as the concentrations of reactants decrease.</td>
<td>Forward reaction rate increases as the reaction gets going.</td>
</tr>
<tr>
<td></td>
<td>(b) reverse reaction Reverse reaction rate is the same as the forward rate.</td>
</tr>
<tr>
<td></td>
<td>(i) is initially zero</td>
</tr>
<tr>
<td></td>
<td>(ii) increases as the concentration of products increase.</td>
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<tr>
<td><strong>CHARACTERISTICS OF EQUILIBRIUM</strong></td>
<td></td>
</tr>
<tr>
<td>3. After equilibrium has been established, the concentrations of all the species remain constant with time.</td>
<td></td>
</tr>
<tr>
<td>4. At equilibrium, the concentrations of reactants and products are related by the equilibrium law (K=\frac{[\text{NOCl}]^2}{[\text{NO}]^2[\text{Cl}_2]})</td>
<td>There is a simple arithmetical relationship between the concentrations of reactants and products.</td>
</tr>
<tr>
<td>5. A large equilibrium constant indicates that the equilibrium concentration of products are large relative to the concentrations of reactants; a small equilibrium constant indicates that the equilibrium concentration of products are small relative to the concentration of reactants.</td>
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</tr>
<tr>
<td>6. At equilibrium the forward and reverse reactions (a) continue to occur (b) have equal rates.</td>
<td></td>
</tr>
<tr>
<td><strong>CHANGING EQUILIBRIUM CONDITIONS</strong></td>
<td></td>
</tr>
<tr>
<td>7. Le Châtelier’s principle. If a system is a chemical equilibrium, and some change is made to the conditions, the system adjusts to reestablish</td>
<td></td>
</tr>
</tbody>
</table>
equilibrium in such a way as to partially counteract the imposed change.

**Changing the concentration of one of the reacting species**

After equilibrium has been achieved the [NO] is instantaneously increased (but the volume remains unchanged).

8. The concentrations changed in such a way that they partially counteract the imposed change (an increase in [NO]). Thus, the system adjusts to reduce the [NO]; the [NO] and [Cl₂] decrease and the [NOCl] increases.

9. When equilibrium is reestablished the
   (a) [NO] will be
       (i) less than its adjusted value
       (ii) higher than its initial equilibrium value
   (b) [Cl₂] will be less than its initial equilibrium value
   (c) [NOCl] will be greater than its initial equilibrium value.

10. When the [NO] is increased, the rate of the
    (a) forward reaction will instantaneously increase
    (b) reverse reaction will
        (i) be initially unchanged
        (ii) gradually increase.

11. When equilibrium is reestablished, the rate of the
    (a) forward and reverse reactions will be equal
    (b) forward and reverse reactions will be greater than at the initial equilibrium.

12. When equilibrium is reestablished, the equilibrium constant is the same as under the conditions.

**Changing the temperature of the system**

After equilibrium has been achieved the temperature is instantaneously increased (but the volume remains unchanged).

13. The concentrations changed in such a way that they partially counteract the imposed change (an increase in temperature). Thus, the system adjusts to favor the endothermic
reaction; the [NO] and [Cl₂] increase and the [NOCl] decreases.

14. When equilibrium is reestablished the
(a) [NO] will be greater than its initial equilibrium value
(b) [Cl₂] will be greater than its initial equilibrium value
(c) [NOCl] will be less than its initial equilibrium value.

15. When the temperature is increased the rate of the
(a) forward reaction will increase
(b) reverse reaction will increase
(c) reverse reaction will be greater than the rate of the forward reaction.

16. When equilibrium is reestablished, the rate of the
(a) forward and reverse reactions will be equal
(b) forward and reverse reactions will be greater than at the initial equilibrium.

17. When equilibrium is reestablished the equilibrium constant is smaller than under the initial conditions.

Changing the volume of the system (or the pressure of the system)
After equilibrium has been achieved, the volume of the system is decreased (but the temperature remains unchanged).

18. The concentrations of all gaseous species in the system will instantaneously increase.

19. The concentrations change in such a way that they partially counteract the imposed change (an increase in the concentration of gaseous particles). Thus, the system adjusts to favor the reaction producing the smaller number of gaseous particles; the [NOCl] increases and the [NO] and [Cl₂] decrease.

20. When equilibrium is reestablished the
(a) [NO] will be less than its adjusted value
(b) [Cl₂] will be less than its adjusted value
(c) [NOCl] will be greater than its adjusted value.
| 21. When the volume is decreased, the rate of the | (a) forward reaction increases | When the volume is decreased the rate of the reverse reaction is decreased.  
| | (b) reverse reaction increases |  
| | (c) forward reaction will be greater than the rate of the reverse reaction. |  
| 22. When equilibrium is reestablished, the rate of the | (a) forward and reverse reactions will be equal | When equilibrium is reestablished the rates of the forward and reverse reactions will be equal to those at the initial equilibrium.  
| | (b) forward and reverse reactions will be greater than at the initial equilibrium. |  
| 23. When equilibrium is reestablished, the equilibrium constant is the same as under the initial conditions. | When the volume is decreased and equilibrium is reestablished the equilibrium constant is greater than under the initial conditions.  
| Adding a catalyst | After equilibrium has been achieved, a catalyst is added to the system. |  
| 24. The rate of the | (a) forward reaction is increased | A catalyst can affect the rates of the forward and reverse reactions differently.  
| | (b) reverse reaction is increased |  
| | (c) forward and reverse reactions are equal. |  
| 25. The concentration of | (a) [NO] is unchanged |  
| | (b) [Cl₂] is unchanged |  
| | (c) [NOCl] is unchanged. |  
| 26. The equilibrium constant is the same as under the initial conditions. | List of propositions from Hacking and Garnett, 1985  
| from Hackling and Garnett, 1985 |
Appendix B

Preliminary work – Pilot Study

Two pilot studies were conducted to develop and test the methodology of the data collection and analysis, and emerging themes arose which were worked into the main study. In the first of the pilot studies, participants included three chemistry teachers who were at different points in their careers, and who had differing expertise levels. One teacher (coded as P17151) has taught high school chemistry at different levels (including AP and IB) over a 15-year career. A second teacher (coded as P15693) began a career teaching New York State Regent’s Chemistry in the high school and is now teaching introductory chemistry in a college after retirement from the high school. The last teacher (coded as P13719) has recently completed college and has not yet had a chance to teach chemistry at a high school level. The three participants were chosen with the idea that they would demonstrate the complete spectrum of understanding within the concepts of chemical equilibrium and reaction rates.

In this pilot study, information about knowledge of chemical equilibrium and how it can be explained was collected in two ways. First, the participants were interviewed to probe their understanding of the approach to equilibrium, the equilibrium condition, changes to a system at equilibrium, and the addition of a catalyst. All questions were based on the exothermic reaction, \( 2\text{NO}(g) + \text{O}_2(g) \rightleftharpoons 2\text{NO}_2(g) \). An interview guide approach was used, and after their initial answers to questions, participants were asked to explain why they had answered in that way (Patton, 1990, p. 280). Graphing tasks, which included drawing concentration versus time graphs and rate versus time graphs was completed during the parts of the interview dealing with the approach to equilibrium, changes made to the equilibrium state, and the addition of a catalyst. A Predict-Observe-Explain activity involving the change in glowstick light intensity with changes in temperature was also included. Interviews lasted between 40 minutes and 115 minutes, depending on the participant, and were audio-recorded. After the interviews, participants were asked to answer the 47-item CECT assessment, which was set up as an online survey, using Qualtrics survey software. Interview data was transcribed, read, and coded during three re-readings of the transcripts.

The first research question in this study is concerned with the alternative conceptions of the teachers with respect to chemical equilibrium and reaction rates. As expected, the three teachers differed in the alternative conceptions they maintained, based upon experience in the classroom. The teacher with no classroom experience had no understanding of many of the concepts. A total of twenty-four different alternative conceptions were expressed by the participants during the interviews. Two of three teachers understood that as the reaction approached equilibrium from the mixing of the reactants, the rate of the forward reaction would decrease, and the rate of the reverse reaction would increase, due to the relative amounts of collisions between reactants and products. The third teacher maintained the alternative conception that the rate of the forward reaction increases and the rate of the reverse reaction decreases upon approach to equilibrium, and that the rate of the favored reaction is increased. Several alternative conceptions were expressed regarding the characteristics of chemical equilibrium. These alternative conceptions concerned the meaning of the double arrow in the reaction, the relative amounts of reactants and products at equilibrium, the equilibrium condition, and the rates of the forward and reverse reactions.
1. Upon being questioned about the meaning of the double arrow in the equilibrium reaction (⇌), two of the three teachers indicated that since the arrows were of equal length, that was what constituted an equilibrium reaction.

2. Two of three teachers understood that at equilibrium, product would be present along with reactants. Both indicated that the equilibrium constant would dictate the relative concentrations of the mixture at equilibrium. Only the least experienced teacher expressed that at equilibrium, the amount of products were equal to the amount of reactants, a common alternative conception.

3. It was also suggested by this teacher that the forward reaction finishes before the reverse reaction occurs, and that the reaction oscillates back and forth at equilibrium:

By far, the most alternative conceptions held by these teachers related to what happens to the concentrations of reactants and products, and what happens to the forward and reverse reaction rates after the system is disturbed from equilibrium. The three teachers knew well what changes could be made to the system to produce more NO₂. However, when asked to explain or to draw a graph expressing how these changes affected the concentrations and rates of reaction, alternative conceptions were exposed.

1. When asked how more NO₂ could be formed, P17151 correctly suggested that a removal of NO₂ would shift the reaction to produce more of the product. When asked how the rates of the forward and reverse reactions were affected, he erroneously said that the reactants would continue to react at the same rate.

2. When asked what would happen to the concentrations of the reactants and products when NO was added, one teacher said that no change to the O₂ concentration would be observed, and that the concentration of NO would decrease back to the level of the O₂. Upon further reflection, he concluded that the concentration of NO would not decrease, and that the concentration of NO₂ would rise to meet the NO concentration:

It was determined that the results of the interviews impacted the results on the CECT. Therefore, the major change made to the design of the study was that participants will answer the assessment first to get their initial ideas about equilibrium and reaction rates before the graphing tasks of the interview caused any conceptual change. Also, the interview was restructured to specifically glean an initial response, an explanation response, and a graphing response. In addition, extra question about the addition of water was added for interest, and the POE was removed.

The second pilot study was completed to ensure that the changes made to the interview guide produced the desired information. The participant was a high school teacher (coded as P22138) has taught high school chemistry at different levels (including AP). It was found during this interview, that the revised interview guide would elicit an initial response, an explanation response, and a graphing response from the teacher. Also, an additional item, prediction of what would happen upon the addition of water, worked well. Finally, it was determined that having the teacher answer the CECT survey a few days before the interview resulted in the ability to discuss the incorrect answers during the interview.
Appendix C
IRB Approval Document and Consent Form.

Thank you for your submission of Continuing Review/Progress Report materials for this research study. Stony Brook University IRB (CORIHS B) (FWA #0000125) has APPROVED your submission.

You are reminded that:

1. Your approval to conduct this research will expire on October 21, 2019. You must apply for and be granted continued approval for this study before that date in order to be able to conduct your study in an uninterrupted manner. If you do not receive approval before this date, you must cease and desist all research involving human subjects, their tissue and their data until such time as approval is granted.
2. All research must be conducted in accordance with this approved submission. Any modifications to the study as approved must be reviewed and approved by CORIHS prior to initiation.
3. Unanticipated problems (including serious adverse events) must be reported to the Office of Research Compliance in accordance with SBU Policy at http://research.stonybrook.edu/human-subjects-standard-operating-procedures/unanticipated-problems-involving-risks-subjects-or.
4. Any complaints from subjects or issues of non-compliance must be immediately reported to the Office of Research Compliance.
5. Consent forms signed by subjects in this study must be kept by the investigator for 7 (seven) years from study termination, or indefinitely (if so indicated in the consent form).
6. Study is approved for data analysis only.
If you have any questions or comments about this correspondence, please contact (include your study title and CORIHS number):
Office of Research Compliance
Division of Human Subject Protections
Stony Brook University
Stony Brook, NY 11794-3368.
Phone: 631-632-9036
Fax: 631-632-9839

We are interested in receiving feedback regarding your experience with the Office of Research Compliance, SBU’s IRBs (CORIHS), or any other aspect of our Human Research Protection Program. Please feel free to e-mail Margaret McNurian, Interim Assistant Vice President for Research Compliance, at Margaret.Mcnurian@stonybrook.edu.
RESEARCH CONSENT FORM

Project Title: Teachers’ conceptions about chemical equilibrium in terms of rates of reaction

Principal Investigator: Keith Sheppard, Ed. D.
Co-Investigators: Stacey Greengold, doctoral student
Department: Center for Science and Mathematics Education, Stony Brook University

You are being asked to be a volunteer in a research study.

PURPOSE

The purpose of this study is:

- The purpose of this study is to examine teachers’ conceptual understanding of chemical equilibrium, as well as how teachers present chemical equilibrium in their classes.
- It is important to explore how teachers think about the topics they teach, and how these topics are presented in their classrooms.
- This study will be useful in helping to improve teacher preparation programs and professional development programs for chemistry teachers.
- You were chosen as a potential participant for this study because you are a college or high school chemistry teacher in New York State who teaches advanced chemistry classes.
- There will be approximately 12-15 participants in this study.

PROCEDURES

If you decide to be in this study, your part will involve:

- an online assessment that deals with the concepts of chemical equilibrium. A brief survey of your educational and teaching background is included. This should take about 20-30 minutes to complete,
- an interview, dealing with (a) the concepts of chemical equilibrium and (b) how you present it in your classroom. The interview will take about one hour, and will be audio-taped.
RISKS / DISCOMFORTS
The following risks/discomforts may occur as a result of you being in this study:

- There are no foreseeable risks or discomforts associated with your participation in this study.

BENEFITS
- There is no direct benefit expected as a result of you being in this study.

PAYMENT TO YOU
- There is no payment to you for participation in this study.

CONFIDENTIALITY
We will take steps to help make sure that all the information we get about you is kept confidential. Your name will not be used wherever possible. We will use a code instead. All the study data that we get from you will be kept locked up. The code will be locked up too. If any papers and talks are given about this research, your name will not be used. All audiotapes of interviews will be deleted two years after transcription.

We want to make sure that this study is being done correctly and that your rights and welfare are being protected. For this reason, we will share the data we get from you in this study with the study team, Stony Brook University’s Committee on Research Involving Human Subjects, applicable institutional officials, and certain federal offices, including the Office for Human Research Protections (OHRP). However, if you tell us you are going to hurt yourself, hurt someone else, or if we believe the safety of a child is at risk, we will have to report this. In a lawsuit, a judge can make us give him the information we collected about you.

COSTS TO YOU
- There is no cost to you for participation in this study.

ALTERNATIVES
- Your alternative to being in this study is to simply not participate.

YOUR RIGHTS AS A RESEARCH SUBJECT
- Your participation in this study is voluntary. You do not have to be in this study if you don’t want to be.
• You have the right to change your mind and leave the study at any time without giving any reason, and without penalty.
• Any new information that may make you change your mind about being in this study will be given to you.
• You will get a copy of this consent form to keep.
• You do not lose any of your legal rights by signing this consent form.

QUESTIONS ABOUT THE STUDY OR YOUR RIGHTS AS A RESEARCH SUBJECT

• If you have any questions, concerns, or complaints about the study, you may contact Stacey Greengold, at telephone # (516-343-8422), or by e-mail at stacey.greengold@stonybrook.edu. You may also contact Keith Sheppard, the principal investigator, at telephone # (631-632-2989), or by email at keith.sheppard@stonybrook.edu.
• If you have any questions about your rights as a research subject or if you would like to obtain information or offer input, you may contact the Stony Brook University Research Subject Advocate, Ms. Lu-Ann Kozlowski, BSN, RN, (631) 632-9036, OR by e-mail, lu-ann.kozlowski@stonybrook.edu
• Visit Stony Brook University’s Community Outreach page, http://www.stonybrook.edu/research/orc/community.shtml for more information about participating in research, frequently asked questions, and an opportunity to provide feedback, comments, or ask questions related to your experience as a research subject.

If you sign below, it means that you have read (or have had read to you) the information given in this consent form, and you would like to be a volunteer in this study.

Subject Name (Printed)                     Subject Signature                     Date

Name of Person Obtaining Consent (printed) Signature of Person Obtaining Consent    Date
Appendix D

Recruitment email.

E-MAIL RECRUITMENT TEXT

From: stacey.greengold@stonybrook.edu
To: (potential participant’s email address)
Subject: SBU Research Study: Request for Chemistry Teacher Participation

Dear

I am a doctoral student in the Science Education Department at Stony Brook University and I am conducting a research study that explores teachers’ conceptions of chemistry topics, and how these topics are presented in their classrooms. It is my intention that this research be used to inform teacher preparation programs and professional development programs for chemistry teachers. I am asking chemistry teachers who have been teaching advanced levels of chemistry (college level, Advanced Placement, IB, etc.) for five years or more to participate in this important research.

If you choose to participate, I will be asking you to take part in an online assessment and an interview. The interview will take approximately an hour, and the assessment will take only 20-30 minutes of your time. I will travel to your school for your participation, or you may choose to visit me at Stony Brook University or Lawrence Woodmere Academy (where I am also an AP Chemistry Teacher). If you choose to participate, your identity will be kept confidential, and you will be required to sign an informed consent form.

The results of my research will be available to you once my work is complete. I have secured approval for research with human subjects from the Institutional Review Board at Stony Brook University (see attachment).

Please take a moment to respond to this email (stacey.greengold@stonybrook.edu), letting me know if you wish to be included in my study. In addition, you can contact me at (516) 343-8422 should you have any questions or concerns about the study.

Thank you very much for your consideration.

Sincerely,

Stacey Greengold, doctoral student
Keith Sheppard, Ed. D., Principal Investigator
Appendix E


Consider the following reaction:
\[ 2\text{NO(g)} + \text{Cl}_2(g) \rightleftharpoons 2\text{NOCl(g)} + \text{heat} \]

1. Equal concentrations of NO and Cl\(_2\) are placed in a closed system and allowed to react. Assuming the reaction does not go to completion, which of the following graphs most probably represents the changes in concentration of the species until equilibrium is achieved?

![Graphs A, B, C, D, E](image)

2. Which of the following pair of graphs best represents the change in rates of the forward (F) and reverse (R) reactions from the mixing of the reactants until equilibrium is achieved?

![Graphs A, B, C, D, E](image)
3. The equilibrium constant (K) for the reaction is equal to

\[ (a) \ K = \frac{[\text{NOCl}]}{[\text{NO}][\text{Cl}_2]} \quad (b) \ K = \frac{[\text{NOCl}]^2}{[\text{NO}]^2[\text{Cl}_2]} \quad (c) \ K = \frac{[\text{NO}]^2[\text{Cl}]}{[\text{NOCl}]^2} \]

\[ (d) \ K = \frac{[\text{NOCl}]^2}{[\text{NO}][\text{Cl}_2]} \quad (e) \ K = \frac{[\text{NOCl}]}{[\text{NO}][\text{Cl}_2]} \]

4. A large equilibrium constant indicates that at equilibrium
   (a) the concentrations of products are large compared with the concentrations of reactants.
   (b) the concentrations of reactants are large compared with the concentrations of products.
   (c) the rate of the forward reaction will be faster than the rate of the reverse reaction.
   (d) the rate of the reverse reaction will be faster than the rate of the forward reaction.

5. Assume K for the reaction was 20 at a particular temperature.
   If the concentrations of each of the species in a particular reaction vessel were:
   \[ [\text{NOCl}] = 2 \text{ mol L}^{-1}, \ [\text{NO}] = 0.1 \text{ mol L}^{-1}, \ \text{and} \ [\text{Cl}_2] = 8 \text{ mol L}^{-1}, \]
   determine whether
   (a) the system is at equilibrium
   (b) the system is not at equilibrium – more products would be formed
   (c) the system is not at equilibrium – more reactants would be formed

For Questions 6-15, answer:

(a) if the statement is true
(b) if the statement is false

When equilibrium is established:

6. the concentrations of all the species remain constant with time.
7. the concentrations of reactants are zero.
8. the concentrations of reactants equal the concentrations of products.
9. the concentration of NO equals the concentration of NOCl.
10. the concentration of reactants and products vary constantly as the reaction oscillates between reactants and products.
11. the concentrations of reactants and products are related through the equilibrium constant.
12. the rates of the forward and reverse reactions are zero.
13. the rates of the forward and reverse reactions are constant but equal.
14. the rates of the forward and reverse reactions are changing but equal.

15. the rates of the forward and reverse reactions are not equal.

Questions 16 through 23 relate to the following:

After equilibrium has been established the concentration of NO is instantaneously increased but the volume and temperature remain constant. When equilibrium is reestablished:

16. The concentration of NO will be
   (a) greater than the adjusted value.
   (b) equal to the adjusted value.
   (c) less than the adjusted value but greater then the initial equilibrium value.
   (d) equal to the initial equilibrium value.
   (e) less than the initial equilibrium value.

17. The concentration of Cl₂ will be
   (a) less than its initial equilibrium value.
   (b) equal to its initial equilibrium value.
   (c) greater than its initial equilibrium value.

18. The concentration of NOCl will be
   (a) less than its initial equilibrium value.
   (b) equal to its initial equilibrium value.
   (c) greater than its initial equilibrium value.

19. When the [NO] is increased the rate of the forward reaction will be instantaneously
   (a) unchanged.
   (b) increased.
   (c) decreased.

20. When the [NO] is increased the rate of the reverse reaction will be instantaneously
   (a) unchanged.
   (b) increased.
   (c) decreased.

21. When the [NO] is increased the rate of the forward reaction will instantaneously be
   (a) equal to the rate of the reverse reaction.
   (b) greater than the rate of the reverse reaction.
   (c) less than the rate of the reverse reaction.
22. When equilibrium is reestablished the rates of the forward and reverse reactions will be
(a) equal to those at the initial equilibrium.
(b) greater than at the initial equilibrium.
(c) less than at the initial equilibrium.

23. When equilibrium is reestablished the value of the equilibrium constant will be
(a) greater than at the initial equilibrium.
(b) less than at the initial equilibrium.
(c) equal to that at the initial equilibrium.

Questions 24 through 31 relate to the following:

After equilibrium has been established the temperature of the system is instantaneously increased but the volume remains unchanged. When equilibrium is reestablished:

24. The concentration of NO will be
(a) less than at the initial equilibrium.
(b) equal to that at the initial equilibrium.
(c) greater than at the initial equilibrium.

25. The concentration of Cl₂ will be
(a) less than at the initial equilibrium.
(b) equal to that at the initial equilibrium.
(c) greater than at the initial equilibrium.

26. The concentration of NOCl will be
(a) less than at the initial equilibrium.
(b) equal to that at the initial equilibrium.
(c) greater than at the initial equilibrium.

27. When the temperature is increased the rate of the forward reaction will be instantaneously
(a) unchanged.
(b) decreased.
(c) increased.

28. When the temperature is increased the rate of the reverse reaction will be instantaneously
(a) unchanged.
(b) decreased.
(c) increased.
29. When the temperature is instantaneously increased the rate of the forward reaction will be
(a) equal to the rate of the reverse reaction.
(b) greater than the rate of the reverse reaction.
(c) less than the rate of the reverse reaction.

30. When equilibrium is reestablished the rates of the forward and reverse reactions will be
(a) equal to those at the initial equilibrium.
(b) greater than at the initial equilibrium.
(c) less than at the initial equilibrium.

31. When the equilibrium is reestablished the value of the equilibrium constant will be
(a) greater than at the initial equilibrium.
(b) less than at the initial equilibrium.
(c) Equal to that at the initial equilibrium.

Questions 32 through 40 relate to the following:
After equilibrium has been achieved the volume of the system is decreased but the temperature remains unchanged.

32. Instantaneously the concentrations of all the species are
(a) unchanged.
(b) increased.
(c) decreased.

When equilibrium is reestablished,

33. The concentration of NO will be
(a) greater than the adjusted value.
(b) less than the adjusted value.
(c) equal to the adjusted value.

34. The concentration of Cl$_2$ will be
(a) greater than the adjusted value.
(b) less than the adjusted value.
(c) equal to the adjusted value.

35. The concentration of NOCl will be
(a) greater than the adjusted value.
(b) less than the adjusted value.
(c) equal to the adjusted value.
36. When the volume is decreased the rate of the forward reaction will be instantaneously
   (a) unchanged.
   (b) increased.
   (c) decreased.

37. When the volume is decreased the rate of the reverse reaction will be instantaneously
   (a) unchanged.
   (b) increased.
   (c) decreased.

38. When the volume is decreased the rate of the forward reaction will be
   (a) equal to the rate of the reverse reaction.
   (b) greater than the rate of the reverse reaction.
   (c) less than the rate of the reverse reaction.

39. When equilibrium is reestablished the rates of the forward and reverse reactions will be
   (a) equal to those at the initial equilibrium.
   (b) greater than at the initial equilibrium.
   (c) less than at the initial equilibrium.

40. When equilibrium is reestablished, the value of the equilibrium constant will be
   (a) greater then at the initial equilibrium.
   (b) less then at the initial equilibrium.
   (c) equal to that at the initial equilibrium.

Questions 41 through 47 relate to the following:

After equilibrium has been achieved a catalyst is added to the system but other conditions remain unchanged. When the catalyst is added to the system:

41. The rate of the forward reaction will be
   (a) unchanged.
   (b) increased.
   (c) decreased.
   (d) either unchanged or increased depending on whether the catalyst favors the forward or reverse reaction.

42. The rate of the reverse reaction will be
   (a) unchanged.
   (b) increased.
   (c) decreased.
   (d) either unchanged or increased depending on whether the catalyst favors the forward or reverse reaction.
43. The rate of the forward reaction will be
   (a) equal to the rate of the reverse reaction.
   (b) greater than the rate of the reverse reaction.
   (c) less than the rate of the reverse reaction.
   (d) either greater or less than the rate of the reverse reaction depending on whether the catalyst favors the forward or reverse reaction.

44. The concentration of NO will be
   (a) less than at the initial equilibrium.
   (b) equal to that at the initial equilibrium.
   (c) greater than at the initial equilibrium.
   (d) greater or less than at the initial equilibrium depending on the effect of the catalyst.

45. The concentration of Cl₂ will be
   (a) less than at the initial equilibrium.
   (b) equal to that at the initial equilibrium.
   (c) greater than at the initial equilibrium.
   (d) greater or less than at the initial equilibrium depending on the effect of the catalyst.

46. The concentration of NOCl will be
   (a) less than at the initial equilibrium.
   (b) equal to that at the initial equilibrium.
   (c) greater than at the initial equilibrium.
   (d) greater or less than at the initial equilibrium depending on the effect of the catalyst.

47. When equilibrium is reestablished the value of the equilibrium constant will be
   (a) greater than at the initial equilibrium.
   (b) less than at the initial equilibrium.
   (c) equal to that at the initial equilibrium.
   (d) greater or less than at the initial equilibrium depending on the effect of the catalyst.
Appendix F

Interview guide for equilibrium and reaction rate conceptions. Questions will proceed in the order that naturally occurs during the interview; other probing questions may be asked. Initial responses (IR), explanation responses (ER) and graphing responses (GR) are noted in grey. Interview duration is about one hour.

Personal information (this is asked in CECT survey, just ask for clarifications, if needed):
1. Tell me about your educational background and degrees.
2. Tell me about teaching certifications you hold. Primary? Secondary?
3. Tell me about the classes you teach. How long have you been teaching AP/IB/college chemistry? What level IB? What textbook do you use for each class?
4. Have you ever been to a professional development workshop that focused on CE?

Provide sheet with chemical reaction \(2\text{NO}(g) + \text{O}_2(g) \rightleftharpoons 2\text{NO}_2(g), \Delta H = -114\text{kJ}\), worksheet, pencils
5. Tell me about this reaction.
   a. How do you know it’s an equilibrium reaction?
   b. Tell me what the double arrow means to you.
6. If I put the two reactants in a jar, what would you notice over time?
7. How would you know that equilibrium has been reached?
8. What is happening with this reaction at equilibrium at a molecular level?
9. **TASK**: 2 moles of NO and 1 mole of \(\text{O}_2\) are added to an empty flask. Draw/explain what is going on at the molecular level before any reaction has occurred.
10. **TASK**: Draw/explain what is going on at the molecular level when equilibrium has been reached.
11. Write the equilibrium expression for this reaction. What does this mean to you?
12. At 230° C, the equilibrium constant is \(6.44 \times 10^5\). What does this mean to you?

13. Beginning with two moles of NO and one mole of \(\text{O}_2\) in a one-liter flask.
   a. Predict what will happen to the concentrations of \(\text{NO}, \text{O}_2, \text{and NO}_2\) as we approach equilibrium. (IR)
   b. Why do you think so? (ER)
   c. **TASK**: Draw/explain a concentration versus time graph for the concentrations of NO, O2, and NO2 from the initial mixing to when equilibrium is reached. (GR)
   d. Predict what will happen to the rates of the forward and reverse reactions as we approach equilibrium? (IR)
   e. Why do you think so? (ER)
   f. **TASK**: Draw/explain a rate versus time graph for this reaction from the initial mixing to when equilibrium is reached. (GR)

14. Assume the reaction is at equilibrium.
   a. Predict what will happen to the concentrations of \(\text{NO}, \text{O}_2, \text{and NO}_2\) if I suddenly add more NO. (IR)
   b. Why do you think so? (ER)
   c. **TASK**: Continue/explain the graph for the concentrations of NO, O2 and NO2
when the NO is added. \( \text{GR} \)

i. \( \text{If not explained} \) How do the concentrations of NO, O\(_2\), and NO\(_2\) change?

ii. When equilibrium is re-established, how do the concentrations of NO, O\(_2\) and NO\(_2\) compare to what they were before the NO was added? \( \text{IR} \)

iii. Why do you think so? \( \text{ER} \)

d. Predict what will happen to the rates of the forward and reverse reactions when the NO is added. \( \text{IR} \)

e. Why do you think so? \( \text{ER} \)

f. **TASK:** Continue/explain the graph for the rates of the forward and reverse reactions when the NO is added. \( \text{GR} \)

i. \( \text{If not explained} \) How do the forward and reverse reaction rates change?

ii. When equilibrium is re-established, how do the rates of the forward and reverse reactions compare to what they were before the NO was added? \( \text{IR} \)

iii. Why do you think so? \( \text{ER} \)

g. What do you think happens to the equilibrium constant when the NO is added? \( \text{IR} \)

h. Why do you think so? \( \text{ER} \)

15. Assume the reaction is at equilibrium again.

a. Predict what will happen to the concentrations of NO, O\(_2\), and NO\(_2\) if I suddenly raise the temperature. \( \text{IR} \)

b. Why do you think so? \( \text{ER} \)

c. **TASK:** Continue/explain the graph for the concentrations of NO, O\(_2\) and NO\(_2\) when the temperature is increased. \( \text{GR} \)

i. \( \text{If not explained} \) How do the concentrations of NO, O\(_2\), and NO\(_2\) change?

ii. When equilibrium is re-established, how do the concentrations of NO, O\(_2\) and NO\(_2\) compare to what they were before the temperature was increased? \( \text{IR} \)

iii. Why do you think so? \( \text{ER} \)

d. Predict what will happen to the rates of the forward and reverse reactions when the temperature is increased. \( \text{IR} \)

e. Why do you think so? \( \text{ER} \)

f. **TASK:** Continue/explain the graph for the rates of the forward and reverse reactions when the temperature is increased. \( \text{GR} \)

i. \( \text{If not explained} \) How do the forward and reverse reaction rates change?

ii. When equilibrium is re-established, how do the rates of the forward and reverse reactions compare to what they were before the temperature was increased? \( \text{IR} \)

iii. Why do you think so? \( \text{ER} \)

g. What do you think happens to the equilibrium constant when the temperature is increased? \( \text{IR} \)

h. Why do you think so? \( \text{ER} \)
16. Assume the reaction is at equilibrium again.
   a. Predict what will happen to the concentrations of NO, O₂, and NO₂ if I suddenly
decrease the volume of the container. (IR)
   b. Why do you think so? (ER)
   c. TASK: Continue/explain the graph for the concentrations of NO, O₂ and NO₂
when the volume is decreased. (GR)
      i. *(If not explained)* How do the concentrations of NO, O₂, and NO₂
         change?
      ii. When equilibrium is re-established, how do the concentrations of NO, O₂
          and NO₂ compare to what they were before the volume was decreased? (IR)
      iii. Why do you think so? (ER)
   d. Predict what will happen to the rates of the forward and reverse reactions when
the volume is decreased. (IR)
   e. Why do you think so? (ER)
   f. TASK: Continue/explain the graph for the rates of the forward and reverse
reactions when the volume is decreased. (GR)
      i. *(If not explained)* How do the forward and reverse reaction rates change?
      ii. When equilibrium is re-established, how do the rates of the forward and
          reverse reactions compare to what they were before the volume was decreased? (IR)
      iii. Why do you think so? (ER)
   g. What do you think happens to the equilibrium constant when the volume is
decreased? (IR)
   h. Why do you think so? (ER)

17. Assume the reaction is at equilibrium again.
   a. Predict what will happen to the concentrations of NO, O₂, and NO₂ if I add a
catalyst to the system. (IR)
   b. Why do you think so? (ER)
   c. TASK: Continue/explain the graph for the concentrations of NO, O₂ and NO₂
when the catalyst is added. (GR)
      i. *(If not explained)* How do the concentrations of NO, O₂, and NO₂
         change?
      ii. When equilibrium is re-established, how do the concentrations of NO, O₂
          and NO₂ compare to what they were before the catalyst was added? (IR)
      iii. Why do you think so? (ER)
   d. Predict what will happen to the rates of the forward and reverse reactions when
the catalyst is added. (IR)
   e. Why do you think so? (ER)
   f. TASK: Continue/explain the graph for the rates of the forward and reverse
reactions when the catalyst is added. (GR)
      i. *(If not explained)* How do the forward and reverse reaction rates change?
      ii. When equilibrium is re-established, how do the rates of the forward and
          reverse reactions compare to what they were before the catalyst was added? (IR)
iii. Why do you think so? (ER)

g. What do you think happens to the equilibrium constant when the catalyst is added? (IR)

h. Why do you think so? (ER)

18. Assume the reaction is at equilibrium again.
   a. Predict what will happen to the concentrations of NO, O₂, and NO₂ if I add water to the system. (IR)
   b. Why do you think so? (ER)
   c. TASK: Continue/explain the graph for the concentrations of NO, O₂ and NO₂ when the water is added. (GR)
      i. (If not explained) How do the concentrations of NO, O₂, and NO₂ change?
      ii. When equilibrium is re-established, how do the concentrations of NO, O₂ and NO₂ compare to what they were before the water was added? (IR)
      iii. Why do you think so? (ER)
   d. Predict what will happen to the rates of the forward and reverse reactions when the water is added. (IR)
   e. Why do you think so? (ER)
   f. TASK: Continue/explain the graph for the rates of the forward and reverse reactions when the water is added. (GR)
      i. (If not explained) How do the forward and reverse reaction rates change?
      ii. When equilibrium is re-established, how do the rates of the forward and reverse reactions compare to what they were before the water was added? (IR)
      iii. Why do you think so? (ER)
   g. What do you think happens to the equilibrium constant when the water is added? (IR)
   h. Why do you think so? (ER)

19. Tell me about equilibrium and rates in your class.
   a. How do you typically teach the concepts of equilibrium?
      i. in terms of rates?
      ii. in terms of LCP?
      iii. math only?
   b. What misconceptions do you notice that your students have about equilibrium?

20. We’ve spoken a lot about equilibrium. Anything else you’d like to add?
### Appendix G

Required responses for SU coding of interview data.

<table>
<thead>
<tr>
<th>Question</th>
<th>Required response for SU coding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Describe reaction</td>
<td>reversible/equilibrium/r\textsubscript{f} = r\textsubscript{i}, indication of stoichiometry, exothermic, closed system</td>
</tr>
<tr>
<td>How do you know this is an equilibrium reaction?</td>
<td>equilibrium arrow stands for reversibility (or participant has seen reaction/in textbook and can explain macroscopic changes that describe the equilibrium state)</td>
</tr>
<tr>
<td>What would happen if NO and O\textsubscript{2} were added to a flask and allowed to react?</td>
<td>color change, formation of NO\textsubscript{2}, at equilibrium all three species present, indication of dynamic equilibrium</td>
</tr>
<tr>
<td>How would you know that equilibrium has been reached?</td>
<td>color persistence/appears static</td>
</tr>
<tr>
<td>What is happening on a molecular level at equilibrium?</td>
<td>constant collisions, indication of dynamic equilibrium</td>
</tr>
<tr>
<td><strong>TASK</strong>: drawing before reaction has begun</td>
<td>only NO and O\textsubscript{2} particles drawn, mixed, ratio of 2:1, N and O drawn differently, gases (fill container), more than 2 molecules of NO shown, more than 1 molecule of O\textsubscript{2} shown, O\textsubscript{2} diatomic, random orientations</td>
</tr>
<tr>
<td><strong>TASK</strong>: drawing at equilibrium</td>
<td>NO, O\textsubscript{2}, and NO\textsubscript{2} particles drawn, mixed, fill container, asked about or assumed K reflected in diagram, reaction stoichiometry indicated, no simple stoichiometric relationship between reactants and products at equilibrium</td>
</tr>
<tr>
<td>Write the equilibrium expression.</td>
<td>( K = \frac{[\text{NO}_2]^2}{[\text{NO}]^2[\text{O}_2]} )</td>
</tr>
<tr>
<td>What does equilibrium constant mean?</td>
<td>relationship between concentrations of all species at equilibrium, different equilibrium states, different concentrations, but constant K</td>
</tr>
<tr>
<td>What does the large equilibrium constant provided mean?</td>
<td>At equilibrium, the ratio of [products] to [reactants] is &gt;1/equilibrium favors products/at equilibrium, [products] &gt; [reactants]</td>
</tr>
<tr>
<td>Prediction: NO and O\textsubscript{2} added to flask. What happens to [NO], [O\textsubscript{2}], and [NO\textsubscript{2}] as equilibrium is approached?</td>
<td>[NO] and [O\textsubscript{2}] decrease, [NO\textsubscript{2}] increases</td>
</tr>
<tr>
<td>Explanation: NO and O\textsubscript{2} added to</td>
<td>[NO] and [O\textsubscript{2}] decrease as they are consumed; reaction</td>
</tr>
</tbody>
</table>
flask. What happens to $[\text{NO}]$, $[\text{O}_2]$, and $[\text{NO}_2]$ as equilibrium is approached? produces $\text{NO}_2$ and $[\text{NO}_2]$ increases; eventual plateau as reactions occur simultaneously

Graph: NO and $\text{O}_2$ added to flask. What happens to $[\text{NO}]$, $[\text{O}_2]$, and $[\text{NO}_2]$ as equilibrium is approached?

[NO] and $[\text{O}_2]$ concentrations begin $>0$; starting amounts have correct placement on graph; $[\text{NO}_2]$ increases from zero; [NO] and $[\text{O}_2]$ immediately decrease; indication of comparative rate of decrease; concentrations level off at equilibrium; at equilibrium, all concentrations are constant; overall shape of graph is correct; no simple arithmetic relationship between products/reactants is indicated. Lines level off at equilibrium.

Prediction: NO and $\text{O}_2$ added to flask. What happens to $r_f$ and $r_r$ as equilibrium is approached?

$r_f$ decreases; $r_r$ increases; at equilibrium $r_f = r_r$

Explanation: NO and $\text{O}_2$ added to flask. What happens to $r_f$ and $r_r$ as equilibrium is approached?

$r_f$ decreases as reactants get consumed and less collisions occur; $r_r$ increases as products form and more collisions occur; at equilibrium collisions occur simultaneously

Graph: NO and $\text{O}_2$ added to flask. What happens to $r_f$ and $r_r$ as equilibrium is approached?

$r_f$ starts high and decreases, $r_r$ starts at zero and increases, at equilibrium $r_f = r_r$, overall shape of graph is correct

Prediction: What happens to the concentrations of reactants and products after adding additional NO to the system at equilibrium?

[NO] spikes, then decreases; $[\text{O}_2]$ decreases; $[\text{NO}_2]$ increases; at equilibrium, all concentrations remain constant again. Okay if no spike, but it is on graph.

Explanation: What happens to the concentrations of reactants and products after adding additional NO to the system at equilibrium?

an increase in [NO] increases the number of collisions between reactants, thus, more product is formed as reactants are consumed; [NO] at new equilibrium is higher than [NO] at the initial equilibrium because there are more particles in the system

Graph: What happens to the concentrations of reactants and products after adding additional NO to the system at equilibrium?

spike in [NO], then decreases and levels off lower than adjusted value, but higher than initial equilibrium. $[\text{O}_2]$ decreases, levels off lower than initial equilibrium. $[\text{NO}_2]$ increases, levels off higher than initial equilibrium. At equilibrium, all concentrations constant. Overall shape of graph is correct.

Prediction: What happens to the $r_f$ and $r_f$ after adding additional NO

$r_f$ will instantaneously increase; $r_r$ will increase to meet
<table>
<thead>
<tr>
<th>Explanation: What happens to the ( r_f ) and ( r_r ) after adding additional NO to the system at equilibrium?</th>
<th>( r_f ) (both will increase)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explanation: What happens to the ( r_f ) and ( r_r ) after adding additional NO to the system at equilibrium?</td>
<td>additional NO instantly creates more collisions between reactants, increasing ( r_f ) instantly; ( r_r ) will begin to increase as more products are formed and more collisions occur, at equilibrium, ( r_f = r_r )</td>
</tr>
<tr>
<td>Graph: What happens to the ( r_f ) and ( r_r ) after adding additional NO to the system at equilibrium?</td>
<td>sharp increase in ( r_f ) then decreases, no instantaneous change in ( r_r ), then increases. Both rates are higher than at initial equilibrium. Overall shape of graph is correct.</td>
</tr>
<tr>
<td>When equilibrium is re-established, how does the ( r_f ) and ( r_r ) compare to what they were before the NO was added?</td>
<td>( r_f ) and ( r_r ) would be higher due to a higher number of particles in the system; still equal to each other</td>
</tr>
<tr>
<td>What happened to the K when the NO was added?</td>
<td>remains the same</td>
</tr>
<tr>
<td>Prediction: What happens to the concentrations of reactants and products after increasing the temperature of the system?</td>
<td>[NO] increases; [O(_2)] increases; [NO(_2)] decreases</td>
</tr>
<tr>
<td>Explanation: What happens to the concentrations of reactants and products after increasing the temperature of the system?</td>
<td>both reactions gain more kinetic energy and more particles can meet EA; a higher percentage of products meet EA; Arrhenius Equation; Boltzmann distribution</td>
</tr>
<tr>
<td>Graph: What happens to the concentrations of reactants and products after increasing the temperature of the system?</td>
<td>[NO] increases and levels off higher than initial equilibrium; [O(_2)] increases and levels off higher than initial equilibrium; [NO(_2)] decreases and levels off lower than initial equilibrium; At equilibrium, all concentrations constant. Overall shape of graph is correct.</td>
</tr>
<tr>
<td>When equilibrium is re-established, how do the [NO], [O(_2)] and [NO(_2)] compare to what they were before the temperature was increased?</td>
<td>[NO] would be higher. [O(_2)] would be higher. [NO(_2)] would be lower.</td>
</tr>
<tr>
<td>Prediction: What happens to ( r_f ) and ( r_r ) after increasing the temperature of the system?</td>
<td>both ( r_f ) and ( r_r ) will instantaneously increase; ( r_f ) will increase ( &gt; ) ( r_r )</td>
</tr>
<tr>
<td>Explanation: What happens to ( r_f ) and ( r_r ) after increasing the</td>
<td>both increase, but ( r_f ) increases more. Forward reaction has lower activation energy, and a higher percentage of the products have minimum energy to react, therefore</td>
</tr>
<tr>
<td>Question</td>
<td>Answer</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>temperature of the system?</td>
<td>reverse is favored. (percentage of collisions affected by the increase in T is greater on the product side, because $E_A$ is higher)</td>
</tr>
<tr>
<td><strong>Graph: What happens to $r_r$ and $r_f$ after increasing the temperature of the system?</strong></td>
<td>Instantaneous increase in both rates, but $r_r &gt; r_f$; $r_r$ decreases; $r_f$ increases; level off higher than at the initial equilibrium. Overall shape of graph is correct.</td>
</tr>
<tr>
<td>When equilibrium is re-established, how do the $r_r$ and $r_f$ compare to what they were before the temperature was increased?</td>
<td>$r_r$ and $r_f$ would be higher, but equal to each other</td>
</tr>
<tr>
<td><strong>What happened to the K when the temperature was increased?</strong></td>
<td>Decreases</td>
</tr>
<tr>
<td><strong>Prediction: What happens to the concentrations of reactants and products after decreasing the volume of the system?</strong></td>
<td>All concentrations instantaneously increase; as reaction proceeds, $[NO]$ and $[O_2]$ decrease and $[NO_2]$ increases.</td>
</tr>
<tr>
<td><strong>Explanation: What happens to the concentrations of reactants and products after decreasing the volume of the system?</strong></td>
<td>Decreasing the volume instantaneously increases all species' concentrations. More collisions occur between reactants, because there are relatively more particles, drives reaction forward, consuming some of the reactants, and producing products. At equilibrium, all concentrations remain constant again. Partial pressure explanation ok, but not LCP</td>
</tr>
<tr>
<td><strong>Graph: What happens to the concentrations of reactants and products after decreasing the volume of the system?</strong></td>
<td>Spike in all three concentrations, $[NO]$ then decreases and levels off lower than adjusted value, but higher than initial equilibrium. $[O_2]$ decreases, levels off lower than adjusted value, but higher than initial equilibrium. $[NO_2]$ increases, levels off higher than initial equilibrium and higher than adjusted value. At equilibrium, all concentrations constant. Overall shape of graph is correct.</td>
</tr>
<tr>
<td>When equilibrium is re-established, how do the $[NO]$, $[O_2]$ and $[NO_2]$ compare to what they were before the volume was decreased?</td>
<td>$[NO]$ would be higher. $[O_2]$ would be higher. $[NO_2]$ would be higher.</td>
</tr>
<tr>
<td><strong>Prediction: What happens to $r_f$ and $r_r$ after decreasing the volume of the system?</strong></td>
<td>Both $r_f$ and $r_r$ will increase</td>
</tr>
<tr>
<td><strong>Explanation: What happens to $r_f$</strong></td>
<td>Both $r_f$ and $r_r$ will increase as more collisions occur, $r_f$</td>
</tr>
<tr>
<td>Question</td>
<td>Answer</td>
</tr>
<tr>
<td>-------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>and $r_f$ after decreasing the volume of the system?</td>
<td>will initially be $&gt; r_r$ because there are more particles and collisions on reactant side; $r_f$ will decrease as more products are formed; more collisions occur on product side increasing $r_r$, at equilibrium, $r_f = r_r$</td>
</tr>
<tr>
<td>Graph: What happens to $r_f$ and $r_r$ after decreasing the volume of the system?</td>
<td>instantaneous increase in both rates, but $r_f &gt; r_r$; $r_f$ decreases; $r_r$ increases; level off higher than at the initial equilibrium. Overall shape of graph is correct.</td>
</tr>
<tr>
<td>When equilibrium is re-established, how does the $r_f$ and $r_r$ compare to what they were before the volume was decreased?</td>
<td>$r_f$ and $r_r$ would be higher, but equal to each other</td>
</tr>
<tr>
<td>What happened to the $K$ when the volume was decreased?</td>
<td>remains the same</td>
</tr>
<tr>
<td>Prediction: What happens to the concentrations of reactants and products after adding a catalyst to the system?</td>
<td>nothing</td>
</tr>
<tr>
<td>Explanation: What happens to the concentrations of reactants and products after adding a catalyst to the system?</td>
<td>system is already at equilibrium; catalyst only increases the rate of both forward and reverse reactions</td>
</tr>
<tr>
<td>Graph: What happens to the concentrations of reactants and products after adding a catalyst to the system?</td>
<td>no change in graph, constant concentrations</td>
</tr>
<tr>
<td>When equilibrium is re-established, how do the $[NO]$, $[O_2]$ and $[NO_2]$ compare to what they were before the catalyst was added?</td>
<td>they are the same</td>
</tr>
<tr>
<td>Prediction: What happens to $r_f$ and $r_r$ after adding a catalyst to the system?</td>
<td>they would both increase</td>
</tr>
<tr>
<td>Explanation: What happens to $r_f$ and $r_r$ after adding a catalyst to the system?</td>
<td>role of catalyst is to increase the rate of reactions by finding a path to $E_A$</td>
</tr>
<tr>
<td>Graph: What happens to $r_f$ and $r_r$ after adding a catalyst to the system?</td>
<td>rates would both instantaneously increase the same way, overlapping lines (same line for $r_f$ and $r_r$)</td>
</tr>
</tbody>
</table>
system?

When equilibrium is re-established, how does the $r_f$ and $r_s$ compare to what they were before the catalyst was added?

What happened to the $K$ when the catalyst was added?

- they are both higher and equal to each other
- remained the same
Appendix H

**Coding for concentration changes upon mixing of reactants.** SU=sound understanding; PU=partial understanding; PU-AC=partial understanding with a specific alternative conception mentioned; AC=alternative conception; NU=no understanding

<table>
<thead>
<tr>
<th>Prediction: [NO] and [O₂] decrease, [NO₂] increases</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
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</thead>
<tbody>
<tr>
<td>SU</td>
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</tbody>
</table>

**Explanation: [NO] and [O₂] decrease as they get consumed; reaction produces NO₂ and [NO₂] increases**

- • • • • • • • • • • • • •

**Explanation: eventual plateau as both reactions occur simultaneously**

- 

Forward reaction occurs until 2 moles NO₂ are produced *(AC)*

- 

Reverse reaction occurs after the forward reaction has completed *(AC)*

- 

**Explanation Coding**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
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<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU</td>
<td>PU</td>
<td>AC</td>
<td>PU</td>
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<td>PU</td>
<td>PU</td>
<td>PU</td>
<td>PU</td>
<td>SU</td>
<td>PU</td>
<td>PU</td>
<td>PU</td>
</tr>
</tbody>
</table>

**Concentration Graph:**

- [NO], [O₂] start high
- [NO] is twice [O₂]
- [NO] decreases
- [O₂] decreases
- slope O₂=1/2 slope NO
- [NO₂] starts at zero
- [NO₂] increases
- slope NO₂=slope NO (rate of appearance of NO₂=rate of disappearance of NO)
- level off at equilibrium
- [r] and [p] not zero/equal at equilibrium
- graph reflects large K
- overall shape of graph
- immediate decrease in [r]
- immediate increase in [p]
- 2 moles of NO₂ at equilibrium because NO was 2 moles *(AC)*
- at equilibrium, [NO]=[NO₂] due to the coefficients in equation *(AC)*
- NO₂ can not be higher than NO because lines can not cross *(AC)*

**Graph Coding**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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</tr>
</thead>
<tbody>
<tr>
<td>PU</td>
<td>SU</td>
<td>AC</td>
<td>SU</td>
<td>SU</td>
<td>AC</td>
<td>PU</td>
<td>SU</td>
<td>SU</td>
<td>PU</td>
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<td>PU</td>
<td>PU</td>
</tr>
</tbody>
</table>

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## Appendix I

**Coding for rate changes upon mixing of reactants.** SU=sound understanding; PU=partial understanding; PU-AC=partial understanding with a specific alternative conception mentioned; AC=alternative conception; NU=no understanding; $R_f$=rate of the forward reaction; $R_r$=rate of the reverse reaction; *=explained during graphing task

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Prediction:</strong> $R_f$ decreases, $R_r$ increases, become equal at equilibrium</td>
<td>SU</td>
<td>SU</td>
<td>A</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>A</td>
<td>S</td>
<td>A</td>
</tr>
<tr>
<td><strong>Explanation:</strong> $R_f$ decreases as reactants get consumed and less collisions occur</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
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<tr>
<td><strong>Explanation:</strong> $R_r$ increases as more product is made and more collisions occur</td>
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<td><strong>Explanation:</strong> At equilibrium, collisions are occurring simultaneously and at the same rate of occurrence.</td>
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<td>$R_f$ increases as the reaction gets going (AC)</td>
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<td>$R_r$ decreases (AC)</td>
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<td>Reverse reaction occurs after the forward reaction has completed (AC)</td>
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<td>$*r_f$ starts high</td>
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<td>$*r_f$ decreases</td>
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<td>$*r_f$ starts at zero</td>
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<td>$*r_r$ increases</td>
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<td>$*r_f$ at equilibrium, $r_f$ equals $r_r$</td>
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<td>$*overall$ shape of graph</td>
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<td>$R_f$ increases from zero (AC)</td>
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<td>$R_r$ decreases (AC)</td>
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<td>$R_r$ is the same as the $R_f$ (AC)</td>
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<td>reverse reaction begins after forward reaction occurs (AC)</td>
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<td><strong>Graph Coding</strong></td>
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<td>AC</td>
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<td>SU</td>
<td>AC</td>
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Appendix J

Coding for concentration changes upon the addition of NO to the system at equilibrium.
SU=sound understanding; PU=partial understanding; PU-AC=partial understanding with a specific alternative conception mentioned; AC=alternative conception; NU=no understanding; P=only mentioned/drawn when prompted

<table>
<thead>
<tr>
<th>Prediction: [NO] decreases, [O₂] decreases, [NO₂] increases</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
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<table>
<thead>
<tr>
<th>Explanation: The [NO] spikes, and creates more collisions, driving the reaction forward.</th>
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<th>C</th>
<th>D</th>
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<table>
<thead>
<tr>
<th>Explanation: [NO]ₜₐₚ is higher than [NO]ᵢ; since more particles in the system</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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<td>Concentration Graph:</td>
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<td>[NO] spikes (instantaneous increase)</td>
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<td>[NO] decreases</td>
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<td>[NO]ₜₐₚ &gt; [NO]ᵢ</td>
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<td>[O₂] decreases</td>
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<td>[NO₂] increases</td>
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<tr>
<th>Upon reestablishing equilibrium after the addition of NO, the [NO] is lower than at the initial equilibrium. (AC)</th>
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<tr>
<th>Upon reestablishing equilibrium after the addition of NO, all concentrations revert to an arithmetic relationship based on reaction stoichiometry. (AC)</th>
<th>A</th>
<th>B</th>
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<th>Upon reestablishing equilibrium after the addition of NO, it is not possible to determine whether the [NO] is higher, lower, or equal to the initial equilibrium concentration without calculations. (AC)</th>
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Appendix K

Coding for rate changes upon the addition of NO to the system at equilibrium. SU=sound understanding; PU=partial understanding; PU-AC=partial understanding with a specific alternative conception mentioned; AC=alternative conception; NU=no understanding; rf=rate of the forward reaction; rr=rate of the reverse reaction; equil.=equilibrium

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<tbody>
<tr>
<td>rf spikes, then decreases, rf increases to meet rf; final equilibrium rate&gt;initial equilibrium rate</td>
<td>P</td>
<td>U</td>
<td>S</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
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<td>P</td>
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<td>additional NO instantly creates more collisions between reactants, increasing rf instantly</td>
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<td>rf increases as more NO₂ is produced.</td>
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<td>final rate is higher due to higher number of particles in the system</td>
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Le Châtelier’s principle concerns concentrations, but not rates. (AC)

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<th>C</th>
<th>D</th>
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<td>Rate Graph: spike in rf</td>
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<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
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<td>A</td>
<td>C</td>
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<td>rf decreases</td>
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<td>no instantaneous change in rf</td>
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<tr>
<td>rf increases</td>
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<tr>
<td>new equilibrium rate &gt; initial rate</td>
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<tr>
<td>overall shape of graph</td>
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</tr>
</tbody>
</table>

Adding reactant to a system at equil. does not change the rf or rr, because temperature has not changed. (AC)

<table>
<thead>
<tr>
<th>When NO is added to a system at equil., rf increases, but rr decreases, before becoming equal. (AC)</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
</tr>
</tbody>
</table>

When NO is added to a system at equil., rr increases, but rf stays the same. (AC)

When NO is added to a system at equil., the reverse reaction occurs after the forward reaction has completed or proceeded to a certain point. (AC)

When NO is added to a system at equil., rf and rr increase equally. (AC)

Upon reestablishing equilibrium after the addition of NO, rf and rr are equal to what
they were at the initial equilibrium. \((AC)\)

| Graph Coding | S | U | A | C | S | U | A | C | P | U | A | C | P | U | A | C | P | U | A | C |
Appendix L

Coding for concentration changes upon the increase of the temperature of the system at equilibrium. SU=sound understanding; PU=partial understanding; PU-AC=partial understanding with a specific alternative conception mentioned; AC=alternative conception; NU=no understanding

<table>
<thead>
<tr>
<th>Prediction:</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>[NO] and [O2] increase, [NO2] decreases</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Explanation: more energy to break bonds of NO2/meet activation energy of endothermic reaction</td>
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<tr>
<td>Explanation: when T increases, rate of both increase, but higher percentage of products overcome $E_A$ than reactants/ Arrhenius equation/Boltzmann distribution</td>
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<tr>
<td>Explanation: heat treated like product (LCP)</td>
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<tr>
<td>Explanation: rates are affected differently, so K is different (lower)</td>
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<tr>
<td>Kinetics and equilibrium are independent of each other. (AC)</td>
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</table>

**Explanation Coding**

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<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>[NO] increases</td>
<td>P</td>
<td>U</td>
<td>S</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
</tr>
<tr>
<td>[NO2] decreases</td>
<td>P</td>
<td>U</td>
<td>S</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
</tr>
<tr>
<td>at equilibrium, all concentrations remain constant</td>
<td>P</td>
<td>U</td>
<td>S</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
</tr>
<tr>
<td>at equilibrium, concentrations are not equal</td>
<td>P</td>
<td>U</td>
<td>S</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
</tr>
<tr>
<td>overall shape of graph</td>
<td>P</td>
<td>U</td>
<td>S</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
</tr>
<tr>
<td>Upon reestablishing equilibrium after an increase in temperature, all concentrations are equal to what they were at the initial equilibrium. (AC)</td>
<td>P</td>
<td>U</td>
<td>S</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>P</td>
</tr>
<tr>
<td>Graph does not match what is said</td>
<td>S</td>
<td>S</td>
<td>A</td>
<td>S</td>
<td>C</td>
<td>S</td>
<td>S</td>
<td>U</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>U</td>
<td>P</td>
</tr>
</tbody>
</table>
Appendix M

Coding for rate changes upon the increase of the temperature of the system at equilibrium.
SU=sound understanding; PU=partial understanding; PU-AC=partial understanding with a specific alternative conception mentioned; AC=alternative conception; NU=no understanding; rf=rate of the forward reaction; rr=rate of the reverse reaction.

<table>
<thead>
<tr>
<th>Prediction:</th>
<th>Prediction for rate changes upon the increase of the temperature of the system at equilibrium.</th>
<th>AC</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>rf and rr</td>
<td>rf and rr both instantaneously increase (rr more than rf); rf decreases and rr increases to meet at a new, higher rate.</td>
<td></td>
<td>S</td>
<td>S</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>Explanation:</td>
<td>percentage of collisions affected by the increase in T is greater on the product side, because Ea is higher.</td>
<td></td>
<td>S</td>
<td>S</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>instantaneous increase in rr (more than rf)</td>
<td>instantaneous increase in rr (more than rf)</td>
<td></td>
<td>S</td>
<td>S</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>rf increases to equilibrium</td>
<td>rf increases to equilibrium</td>
<td></td>
<td>S</td>
<td>S</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>When the temperature is increased, the rf and rr are increased equally. (AC)</td>
<td>When the temperature is increased, the rf and rr are increased equally. (AC)</td>
<td></td>
<td>S</td>
<td>S</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
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<td>A</td>
<td>C</td>
</tr>
<tr>
<td>When the temperature is increased, rr increases, but rf reaction initially stays constant before increasing. (AC)</td>
<td>When the temperature is increased, rr increases, but rf reaction initially stays constant before increasing. (AC)</td>
<td></td>
<td>S</td>
<td>S</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
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<td>A</td>
<td>C</td>
</tr>
<tr>
<td>When the temperature is increased, the rf increases, but the rf decreases, before becoming equal. (AC)</td>
<td>When the temperature is increased, the rf increases, but the rf decreases, before becoming equal. (AC)</td>
<td></td>
<td>S</td>
<td>S</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>Upon reestablishing equil. after an increase in T, the rf and rr are lower than they were at the initial equil., because K is lower. (AC)</td>
<td>Upon reestablishing equil. after an increase in T, the rf and rr are lower than they were at the initial equil., because K is lower. (AC)</td>
<td></td>
<td>S</td>
<td>S</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>Upon reestablishing equil. after an increase in T, the rf and rr are the same as they were at the initial equil. (AC)</td>
<td>Upon reestablishing equil. after an increase in T, the rf and rr are the same as they were at the initial equil. (AC)</td>
<td></td>
<td>S</td>
<td>S</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>Graph Coding</td>
<td>Graph Coding</td>
<td></td>
<td>S</td>
<td>S</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
</tr>
</tbody>
</table>
Appendix N

Coding for concentration changes upon the decrease of the volume of the system at equilibrium. SU=sound understanding; PU=partial understanding; PU-AC=partial understanding with a specific alternative conception mentioned; AC=alternative conception; NU=no understanding.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Prediction:</strong> [NO₂] increases; [NO], [O₂] decrease</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
</tr>
<tr>
<td><strong>Explanation:</strong> concentration/collisions description</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
</tr>
<tr>
<td><strong>Explanation:</strong> pressure/collisions description</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
</tr>
<tr>
<td><strong>Explanation:</strong> LCP (more moles)</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
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<td>SU</td>
</tr>
<tr>
<td><strong>Explanation:</strong> math (K v Q) or order/rate</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
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<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
<td>SU</td>
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</tbody>
</table>

**Explanation Coding**

- Concentration Graph: spike in all concentrations
- Concentration Graph: decrease in reactants
- Concentration Graph: increase in products
- Concentration Graph: at equilibrium, all concentrations remain constant
- Concentration Graph: at equilibrium, concentrations are not equal
- Concentration Graph: overall shape of graph
- Concentration Graph: no instantaneous increase in concentration when V is decreased (but put the spike in for the NO addition). (AC)
- When the volume is decreased, all concentrations spike up, then decrease, including NO₂. (AC)
- Upon reestablishing equilibrium after a decrease in volume, all concentrations are equal to what they were at the initial equilibrium. (AC)

**Graph Coding**

- P
- U
- A
- C
Appendix O

Coding for rate changes upon the decrease of the volume of the system at equilibrium.
SU=sound understanding; PU=partial understanding; PU-AC=partial understanding with a specific alternative conception mentioned; AC=alternative conception; NU=no understanding; rf=rate of the forward reaction; rr=rate of the reverse reaction; eq.=equilibrium

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
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<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Prediction:</strong></td>
<td>r_f and r_r both instantaneously increase (r_f more than r_r); r_f decreases and r_r increases to meet at a new, higher rate.</td>
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<td>S</td>
<td>S</td>
<td>U</td>
<td>A</td>
<td>C</td>
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<td>U</td>
<td>P</td>
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</tr>
<tr>
<td><strong>Explanation:</strong></td>
<td>difference in collisions</td>
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<td><strong>Explanation:</strong></td>
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<td>A</td>
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<td>S</td>
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<td>P</td>
<td>U</td>
<td>P</td>
<td>U</td>
<td>A</td>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td><strong>Rate Graph:</strong></td>
<td>instantaneous increase in r_f (more than r_r)</td>
<td></td>
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<td></td>
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<tr>
<td>instantaneous increase in r_r</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>r_f decreases to equilibrium</td>
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<td>r_r decreases to equilibrium</td>
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<td>A decrease in volume has no effect on r_f and r_r, since the T is constant. (AC)</td>
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<td>When the volume is decreased, r_f remains constant, and r_f reaction first increases, before becoming equal. (AC)</td>
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<td>When the volume is decreased, r_f increases, but r_r reaction initially stays the same before increasing. (AC)</td>
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<td>When the volume is decreased, only r_f increases instantaneously. (AC)</td>
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<td>When the volume of the system is decreased, r_f increases, but r_r decreases, before becoming equal. (AC)</td>
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<tr>
<td>Upon reestablishing eq. after a decrease in volume, r_f and r_r are the same as they were at the initial equilibrium. (AC)</td>
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<tr>
<td>Upon reestablishing equilibrium after a decrease in volume, r_f and r_r are the same as they were at the initial equilibrium because T is the same. (AC)</td>
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<td><strong>Graph Coding</strong></td>
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160
Appendix P

List of alternative conceptions expressed by the teacher participants during the study.
*described during explanation; G=reflected in the graph drawn for the event.

<table>
<thead>
<tr>
<th>A</th>
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<th>K</th>
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</thead>
<tbody>
<tr>
<td><strong>Alternative conceptions regarding the equilibrium constant, K</strong></td>
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<tr>
<td>1. A large K means reaction will proceed in the forward direction at equilibrium.</td>
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<tr>
<td>2. At equilibrium, some reactant must remain, even if K is large. But only one reactant must remain. The other can get used up.</td>
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<tr>
<td>3. If K decreases, the rate of the forward and reverse reactions decrease.</td>
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<td>4. If K remains constant (addition of NO, decrease in V), then the concentrations of all species when equilibrium is reestablished are the same as at the initial equilibrium.</td>
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</table>

**Alternative conceptions regarding the equilibrium condition**

<table>
<thead>
<tr>
<th>5. There is a simple, mathematical relationship between reactants and products at equilibrium, based on the stoichiometry of the reaction.</th>
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<tbody>
<tr>
<td>6. An equal length double arrow means that the rates of the forward and reverse reactions are equal.</td>
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<td>7. At equilibrium, the forward and reverse reactions oscillate.</td>
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</table>

**Alternative conceptions regarding an approach to equilibrium (mix reactants)**

<table>
<thead>
<tr>
<th>8. The forward reaction occurs until the value of K is reached, then there is no change.</th>
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<td>9. The concentration of products cannot be higher than the concentration of the reactants (lines can not cross).</td>
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</table>
10. When reactants are mixed, the rate of the forward reaction increases as the reaction “gets going”.

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11. When reactants are mixed, the reverse reaction occurs after the forward reaction has completed, or has proceeded to a certain point.

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**Alternative conceptions regarding a change to equilibrium (add reactant)**

12. Upon reestablishing equilibrium after the addition of NO, the concentrations of all species revert to an arithmetic relationship based on reaction stoichiometry.

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13. Upon reestablishing equilibrium after the addition of NO, it is not possible to determine whether the concentration of NO is higher, lower, or equal to the initial equilibrium concentration without completing calculations.

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14. Upon reestablishing equilibrium after the addition of NO, the concentration of all species are the same as they were at the initial equilibrium.

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15. Upon reestablishing equilibrium after the addition of NO, the concentration of NO is lower than it was at the initial equilibrium.

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16. Adding reactant to a system at equilibrium does not change the rate of the forward or reverse reactions, because the temperature has not changed/Changes to the rates of forward and reverse reactions only accompany a change in temperature.

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<tr>
<td>17. When NO is added to the system at equilibrium, the rate of the forward reaction increases, but the rate of reverse reaction decreases, before becoming equal.</td>
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<td>18. When NO is added to the system at equilibrium, the rate of the forward increases, but the reverse rate stays the same.</td>
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<td>19. When NO is added to the system at equilibrium, the reverse reaction occurs after the forward reaction has completed, or has proceeded to a certain point.</td>
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<td>20. When NO is added to the system at equilibrium, the rates of the forward and reverse reactions increase equally.</td>
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<td>21. Upon reestablishing equilibrium after the addition of NO, the rates of the forward and reverse reactions are equal to what they were at the initial equilibrium.</td>
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**Alternative conceptions regarding a change to equilibrium (increase T)**

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<tbody>
<tr>
<td>22. Upon reestablishing equilibrium after an increase in temperature, all concentrations are equal to what they were at the initial equilibrium.</td>
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<tr>
<td>23. When the temperature is increased, the rates of the forward and reverse reactions are increased equally.</td>
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<tr>
<td>24. When the temperature is increased, the rate of the reverse reaction increases, but the rate of the forward reaction initially remains constant before increasing.</td>
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</table>
25. When the temperature is increased, the rate of the reverse reaction increases, but the rate of the forward reaction decreases, before becoming equal.  

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</tr>
</tbody>
</table>

26. Upon reestablishing equilibrium after an increase in temperature, the rates of the forward and reverse reaction are lower than they were at the initial equilibrium, because $K$ is lower.  

<table>
<thead>
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<th>A</th>
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</tr>
</tbody>
</table>

27. Upon reestablishing equilibrium after an increase in temperature, the rates of the forward and reverse reactions are the same as they were at the initial equilibrium.  

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
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</tbody>
</table>

**Alternative conceptions regarding a change to equilibrium (decrease volume)**

28. Volume concentration graph: no instantaneous increase in concentration when $V$ is decreased (but spike for the NO addition).  

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
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</tr>
</tbody>
</table>

29. When the volume is decreased, all concentrations spike up, then all decrease.  

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
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<th>D</th>
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</tbody>
</table>

30. Upon reestablishing equilibrium after a decrease in volume, all concentrations are equal to what they were at the initial equilibrium.  

<table>
<thead>
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<th>B</th>
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</tr>
</tbody>
</table>

31. A decrease in volume has no effect on the rates of the forward and reverse reactions, since the temperature is constant.  

<table>
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<th>A</th>
<th>B</th>
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</tbody>
</table>

32. When the volume is decreased, the rate of the reverse reaction remains constant, and the rate of the forward reaction first increases, before becoming equal.  

<table>
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<th>A</th>
<th>B</th>
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<tr>
<td>33. When the volume is decreased, the rate of the forward reaction increases, but the rate of the reverse reaction initially remains constant before increasing.</td>
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<tr>
<td>34. When the volume is decreased, only the rate of the forward reaction increases instantaneously (spikes).</td>
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<tr>
<td>35. When the volume of the system is decreased, the rate of the forward reaction increases, but the rate of the reverse reaction decreases, before becoming equal.</td>
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<tr>
<td>36. Upon reestablishing equilibrium after a decrease in volume, the rates of the forward and reverse reactions are the same as they were at the initial equilibrium.</td>
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<tr>
<td>37. Upon reestablishing equilibrium after a decrease in volume, the rates of the forward and reverse reactions are lower than they were at the initial equilibrium.</td>
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<tr>
<td>38. Upon reestablishing equilibrium after a decrease in volume, forward and reverse reaction rates are the same as at the initial equilibrium because T has not changed.</td>
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**Alternative conceptions regarding the addition of a catalyst**

<table>
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<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>39. Adding a catalyst to a system at equilibrium does not change the rate of the forward or reverse reactions.</td>
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<td>40. When a catalyst is added to a reaction at equilibrium, there is an increase in the rates of the forward and reverse reactions, but not an</td>
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</table>
41. Upon reestablishing equilibrium after the addition of a catalyst, the rates of the forward and reverse reactions are the same as they were at the initial equilibrium.

<table>
<thead>
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<th>A</th>
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</table>

**Other alternative conceptions**

42. Confusion between moles and molecules/moles and molecules are represented the same way.

<table>
<thead>
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43. Kinetics and equilibrium are independent of each other/treated separately.

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44. Le Châtelier’s principle concerns concentrations, but not rates of reaction.

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45. Adding water to this system would have no effect on the system because water is not part of the equation.

<table>
<thead>
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<th></th>
<th>A</th>
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46. Le Châtelier’s principle explains what happens to a system when the temperature is changed.

<table>
<thead>
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<th>A</th>
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47. Anthropomorphism

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**Total** 4 1 1 5 7 6 1 2 1 4 1 0 7 9 1 3 1 5 1 3 126

166