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INVESTIGATING GRADUATE TEACHING ASSISTANTS' MISCONCEPTIONS IN CHEMICAL EQUILIBRIUM: IMPLICATIONS FOR PEDAGOGICAL SUPPORT

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DIYA TANG
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MISCONCEPTIONS IN CHEMICAL EQUILIBRIUM: IMPLICATIONS FOR

PEDAGOGICAL SUPPORT

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BY THE COMMITTEE CONSISTING OF

Dr. Robyn Beaulieu, Chair

Dr. Oluwatobi Odeleye

Dr. Kelly Feille

Dr. Daniel T. Glatzhofer

Dr. Paul Sims

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Key to Abbreviations

CE	Chemical Equilibrium
CEDT	Chemical Equilibrium Diagnostic Test
GTAs	Graduate Teaching Assistants

Abstract

This study examines the misconceptions about chemical equilibrium held by first-year graduate teaching assistants (GTAs) in a general chemistry course (CHEM 1). To address the research questions, a Chemical Equilibrium Diagnostic Test (CEDT) and a targeted mini-lecture were developed and implemented. Data were collected from two separate cohorts in Spring 2023 (N=10) and Fall 2023 (N=11) through pre- and post-assessments using the CEDT, classroom observations, and follow-up interviews.

Pre-assessment scores averaged 7.10/14 in Spring 2023 and 5.82/14 in Fall 2023, revealing widespread misconceptions, such as misapplying thermodynamic reasoning to predict changes in reaction rate, confusing mass with concentration, and incorrectly applying Le Châtelier's Principle. Among these, 60% of Spring 2023 GTAs incorrectly believed that lowering the temperature shifts an exothermic equilibrium backward, and 36% of Fall 2023 GTAs believed that removing a reactant would cause a passive decrease in another reactant.

Misconceptions were also observed in GTAs' instructional practices during laboratory sessions. For example, one GTA defined equilibrium as the point at which the concentrations of reactants and products are equal, while another incorrectly stated that decreasing pressure shifts equilibrium toward the side with fewer gas molecules. These findings suggest that, without structured guidance, GTAs may unintentionally introduce or reinforce student misconceptions during lab instruction.

Post-assessment scores improved in both cohorts, particularly among mini-lecture attendees. In Spring, attendees improved by 2.5 points while non-attendees by 1.5; in Fall, attendees improved by 2.0 points and non-attendees by 0.66. Although mixed ANOVA results did not show a statistically significant interaction between mini-lecture attendance and score gains, item-level analyses revealed that attendees more frequently corrected specific misconceptions and adopted more precise, IUPAC-aligned terminology.

Interview data (N=4) indicated that GTAs found both the diagnostic test and the mini-lecture helpful. Participants recommended regular content reviews, stronger alignment between lab and lecture materials, and standardized instructional resources to reduce preparation time.

The findings contribute to the broader field of TA training by demonstrating that brief and targeted pedagogical interventions can meaningfully improve GTAs' conceptual understanding and instructional delivery of foundational chemistry topics.

Chapter 1 Introduction

Concepts are the building blocks of our understanding. They represent ideas about what things are and how they work.[1] In contrast, misconceptions are flawed versions of those ideas.[2]

Misconceptions can be found in nearly every corner of daily life. For example, you might believe that coffee comes from beans, when it actually comes from seeds inside the coffee cherry. You might think the phases of the moon are caused by Earth's shadow, but in reality, they result from the moon's position relative to Earth and the sun. Many people also believe that microwaves cook food from the inside out, which is not the case. Another common misconception is that chameleons change color to match their surroundings, when they actually do so for communication, temperature regulation, and emotional expression.

These examples may seem harmless, but they indicate just how common and persistent misconceptions are, especially in science. Throughout my own learning journey, I have often felt like I was trapped in a cycle. I would form a misconception, express it, receive correction, and revise my understanding. Then the process would repeat itself. From primary school to my current experience as a doctoral student and teaching assistant, this pattern has remained with me. Each time I recognize and correct a misconception, I feel a sense of renewal and clarity. This feeling has grown into a genuine interest in understanding misconceptions more deeply.

When I began my doctoral studies at the University of Oklahoma, I also served as a teaching assistant (TA). In my first semester, I enrolled in a course led by my principal investigator, where all TAs were required to take a General Chemistry 1315 (CHEM 1) final exam. I still remember that my group was the only one to achieve a perfect score on the test. That same semester, we were asked to observe each other's classes as part of our training. [2]During these observations, I noticed that some TAs unintentionally conveyed vague or even inaccurate explanations. This experience further shaped my research interest and led me to focus on the misconceptions that TAs may bring into their teaching.

As I mentioned earlier, science is particularly vulnerable to misconceptions because it requires learners to think abstractly, accept ideas that often contradict intuition, and rely on models and evidence rather than everyday experience.[3] Among the sciences, chemistry stands out as a subject filled with subtle and frequent misunderstandings. We often discuss how students bring prior knowledge and alternative conceptions into the chemistry classroom. These misconceptions can be stubborn and can interfere with new learning. But what if the instructors are also bringing in misconceptions? What are the implications when students who already struggle with scientific ideas are taught by instructors who misunderstand those ideas themselves?

These questions became the foundation of my dissertation. I chose to examine the misconceptions that teaching assistants may carry into their classrooms. TAs play a crucial role in shaping students' early experiences in college-level science, yet they are often still learning themselves.

Among the many topics in chemistry, I decided to focus on chemical equilibrium. This topic is known for being especially challenging. It is abstract and counterintuitive, and it depends on a solid understanding of several underlying concepts.[4] As Banerjee notes, teaching chemical equilibrium and thermodynamics has always been difficult due to the high number of conceptual difficulties involved.[5] Because of its complexity and the frequency with which misconceptions occur, chemical equilibrium provides a meaningful context for studying instructor misconceptions. By understanding these misconceptions, we can better support teaching assistants in addressing them and improving their instructional practices.

Chapter 2 Literature Review

2.1 An Overview of Misconception

2.1.1 Definitions of Misconception

The term "misconception" originated in the 17th century, with its first recorded use in the 1660s, defined as "a false opinion, erroneous conception." The word is formed by combining the prefix "mis-" meaning "bad" or "wrong," with "conception," which refers to an idea or notion.[2] While the term itself was established in the 17th century, the systematic study and analysis of misconceptions, particularly in educational contexts, gained prominence in the late 18th century.

Gilbert and Watts summarized the evolution of the definitions of "concepts" and "misconceptions" through different views.[6] The first emerging view, the classical view, considered concepts as static and hierarchical, akin to "logical atoms" with fixed, necessary, and sufficient properties.[7, 8] During this period, misconceptions were defined as errors or deviations from an established, universal "correct" concept.[6]

Over time, the field shifted toward an actional view, seeing concepts as dynamic and continuously reconstructed by learners through their interactions with the environment. As concepts are no longer static but kept changing, Freyberg and Osborne regarded concepts as "ways of organizing experiences," subject to continuous reconstruction and reinterpretation.[9] Misconceptions in the period are valued as steps in cognitive development rather than errors or failures.[6]

In contrast to the classical and actional views, Smith and Medin proposed that "concepts" should be interpreted through an intermediate perspective known as the relational view.[10] This perspective integrates elements of both the classical and actional views, defining concepts as components within a network of interrelated knowledge rather than as discrete entities. For example, the relational view might define a concept like "energy" not just by its individual features but also by its connections to related ideas like force, motion, or conservation. Under this framework, misconceptions are understood as context-dependent and reflective of an individual's degree of understanding within a broader conceptual network. Misconceptions, therefore, are not strictly wrong and may represent valid interpretations within specific contexts or frameworks. Furthermore, Gilbert and Watts argued that the term "pre-conception" aligns with the notion of "misconception" within this view, due to its characteristics of naivety and immaturity in understanding.[6]

As research in this field rapidly developed, many scholars have proposed various definitions of the term "misconception." Phrases such as "prior knowledge," "alternative conceptions," and "naïve beliefs" have frequently been used to characterize and define misconceptions. For instance, Sanger and Greenbowe describe misconceptions as "conceptual and propositional knowledge that is inconsistent with or different from the commonly accepted scientific consensus and is unable to adequately explain observable scientific phenomena."[11] Similarly, Stein et al. define misconceptions as incorrect assumptions that deviate from scientifically accepted ideas.[12] These definitions are consistent with the classical view proposed by Gilbert and Watts.[6]

In addition to these perspectives, diSessa proposes that misconceptions are "deeply held but false prior ideas."[13] The concept of prior knowledge, which refers to the pre-existing knowledge structures learners possess before encountering new instructional content, plays a critical role in understanding misconceptions. According to Shing and Brod, prior knowledge significantly influences how new information is interpreted and integrated.[14] When this prior knowledge aligns with accurate concepts, it facilitates learning; however, if inaccuracies exist, it can hinder students' understanding and impede learning.[15] Some researchers prefer to use the term alternative conceptions instead of "prior knowledge" when discussing misconceptions. For example, Piquette and Heikkinen argue that misconceptions arise from pre-existing alternative conceptions that require restructuring to form scientifically accurate schemas.[16] Alternate conceptions need instructional interventions to facilitate conceptual change.

Another view links misconceptions to naïve science, suggesting that individuals acquire concepts in an intuitive fashion through personal trial-and-error experiences.[17] From this standpoint, misconceptions are defined as naïve beliefs that emerge due to a lack of exposure to scientific knowledge.[18, 19]

In this study, I would like to define misconceptions as “understandings or explanations that differ from what is known to be scientifically correct.”[20]

2.1.2 Characteristics of Misconception

Misconceptions form due to a variety of factors, particularly through learners' interactions with their environment and exposure to information. These misconceptions exhibit distinctive characteristics that have been extensively examined in educational research literature.

Sungur et al. summarize that misconceptions are significantly resistant to change and persist stubbornly in an individual's thinking, becoming deeply embedded in their mental framework.[21] Moreover, they note that these incorrect understandings prove difficult to eliminate, continuing to influence learners' comprehension even when confronted with specifically designed instructional interventions. Chi and Roscoe argue that there are two types of misconceptions, each with distinct characteristics.[22] Some naïve knowledge is easily removed through instruction and should be referred to as "preconceptions," while other naïve knowledge is more robust and highly resistant to change, which should be referred to as "misconceptions."

There is also a debate on whether students' scientifically incorrect ideas are stable and theory-like or fragmented and context-dependent.

In the conceptual framework view, students' misconceptions emerge from well-structured, stable knowledge systems and demonstrate coherence across various phenomena.[23] This perspective emphasizes the unified nature of misconceptions, as evidenced by students' consistent application of incorrect ideas across time and contexts.

Conversely, the "knowledge in pieces" view proposes that misconceptions are fragmentary constructions assembled from smaller, intuitive knowledge elements called phenomenological primitives (p-prims), with students actively modifying these fragmented structures to apply them in new contexts.[24, 25]

Leonard et al. uses the misconception "need drives evolution," such as the belief that cheetahs evolved to run faster because they needed to catch prey, as an example to elaborate these two views.[26] From the perspective of the Conceptual Framework View, this misconception reflects a stable, theory-like framework in which students use the idea that traits arise due to need and are subsequently passed on to offspring to understand evolution. Students would be expected to apply this misconception consistently when analyzing similar scenarios. In contrast, the Knowledge in Pieces View suggests that this misconception might stem from a general, context-dependent intuitive knowledge that "need causes change," which is activated in specific contexts but not others, making it less consistent.

Some researchers have demonstrated that many misconceptions in physics and chemistry are best explained through the conceptual framework view.[27-29] However, contemporary research increasingly suggests that, rather than aligning strictly to one view, both views should be integrated to better explain students' misconceptions.[30, 31]

Now, it is widely recognized that misconceptions are resistant to correction. But why are they so robust? Chi argues that one possible reason for their robustness is students' lack of awareness of their misconceptions.[32]

Additionally, she argues that the misclassification of misconception types can substantially hinder their correction, thus contributing to their persistence.

In her article, Chi adopts an ontological perspective to explain the robustness of certain misconceptions, as opposed to the "knowledge-in-pieces" view or the "conceptual framework" view.[32] The ontological perspective categorizes realities into fundamental kinds, such as entities (e.g., a chair or a tree) and events (e.g., a thunderstorm or a football game), which are differentiated by distinct sets of plausible attributes. According to Chi, robust misconceptions often arise from a mismatch between a student's understanding and the actual ontological category of a phenomenon.[32] For example, students may misconceive heat as a substance or as heat molecules, categorizing it as an entity. In reality, heat is a process, specifically the transfer of energy resulting from the motion of atoms or molecules within a material. This misclassification across ontological categories contributes to the robustness of such misconceptions. In contrast, non-robust misconceptions occur when alternative conceptions remain within the same ontological category and are relatively easy to eliminate.

Chi further illustrates the ontological mismatch by comparing direct processes and emergent processes.[32] A direct process, such as blood circulation, involves components like the heart, blood vessels, and blood interacting in a structured and sequential manner. In contrast, an emergent process, such as diffusion, is one where the global pattern arises from the random, independent interactions of molecules, as seen when several drops of dark blue dye are added to the surface of water. Chi found that students frequently misclassify emergent processes as direct processes because the structured and sequential nature of direct processes aligns more closely with their intuitive understanding. This ontological misclassification makes misconceptions about emergent processes particularly robust and resistant to change.

2.1.3 Addressing Misconceptions

Addressing misconceptions is essential for fostering accurate understanding and meaningful learning in any subject. The first step in overcoming misconceptions is identifying them.[16] Once identified, it's argued that students need to go through the conceptual change to acquire correct concepts.

The conceptual change approach, developed in the 1980s and early 1990s, remains foundational in understanding how learners adopt new ideas.[33] Posner et al. introduced the "conceptual exchange model," which posits that students' pre-instructional conceptions must be fundamentally restructured and replaced by scientific concepts that are incompatible with their prior frameworks.[34]

To enable this exchange, Posner et al. identified four necessary conditions.[34] First, students must experience dissatisfaction with their existing concepts. Second, the new concepts must be intelligible, plausible, and fruitful. Intelligibility requires that the new concept makes sense to the individual, is clearly understood, and is logically coherent. Plausibility means that the new concept must appear reasonable and align with the individual's broader understanding of the world. Lastly, for a concept to be fruitful, it must prove practically useful in solving problems that the old concepts cannot.

However, the "conceptual exchange model" model has its limitations. Hewson critiques this model for its emphasis on the total replacement of old concepts.[35, 36] Hewson proposed the addition of reconcilability to the model, suggesting that new and existing conceptions can coexist and interact, allowing the adoption of new concepts through integration rather than replacement.

As research on conceptual change has rapidly expanded, several criticisms of the traditional conceptual change model have emerged. Fensham argues that the traditional approach focuses narrowly on individual scientific concepts (e.g., force, energy, combustion) without considering the historical and cultural contexts in which these concepts were developed.[37] This lack of attention to the processes of conceptualization and nominalization limits the model's applicability.

Additionally, the classical model has been criticized for its overemphasis on rational and cognitive aspects of learning, particularly logic and scientific reasoning, while neglecting the affective domain. Research has demonstrated that emotional factors, including motivation and personal interests, can significantly influence how students accept new ideas.[33, 38]

Furthermore, some researchers have criticized the classical conceptual change model for adopting a radical constructivist approach that emphasizes internal, individual construction of knowledge while neglecting the social and cultural contexts of learning.[39-41] To address this limitation, it has been argued that multi-perspective frameworks have to be employed. These may include motivational perspectives proposed by Pintrich et al.,[38] the ontological category perspective by Chi et al.,[42] and Vygotsky's socio-cultural theory,[43] etc. Integrating these approaches can provide a more comprehensive understanding of how students can acquire correct scientific concepts.

Extensive research on misconceptions and the conceptual change model offers valuable insights into science teaching and learning. These findings provide educators with practical guidance on effectively addressing students' misconceptions. Leonard et al. suggest that instructors could consider the following steps: 1) identify and understand students' misconceptions; 2) examine the effects of "hot" cognitive and affective factors; 3) design targeted teaching strategies to promote conceptual change; and 4) provide the necessary support for instructors to implement these strategies.[26]

When addressing misconceptions, it is crucial for teachers to understand their origins and structures. If misconceptions are identified as stable and theory-like, instructional approaches should aim to challenge or replace these frameworks to help students acquire scientific understanding. Conversely, if misconceptions are recognized as p-prims, teaching should focus on refining and reorganizing these fragmented ideas into expert understanding rather than eliminating them.[44]

Additionally, some educators may focus too heavily on cognitive and rational ("cold") processes, overlooking the importance of motivational and contextual ("hot") factors. Incorporating motivational elements such as goals, values, self-efficacy, and control beliefs can make the process of conceptual change more effective. For example, teachers can provide students with the background and reasoning behind scientific discoveries to make concepts more relatable and easier to understand.[37] Instructors can also connect content to students' personal lives, interests, or future goals to ignite their curiosity and engagement. Moreover, teachers are encouraged to introduce metacognitive tools such as organization, elaboration, and self-regulation to deepen students' understanding and foster active self-monitoring of their learning progress.[38] By addressing both cognitive and affective dimensions, educators can create a more comprehensive and impactful approach to address students' misconceptions.

So far, I have explored research that examines the definitions and characteristics of misconceptions, as well as cognitive models for addressing them. While these studies offer valuable pedagogical suggestions, many teachers still perceive educational research as irrelevant or inaccessible to their daily classroom practice.[45, 46] However, educational research is essential for helping instructors design effective teaching strategies, as it provides evidence-based insights into how students learn and addresses misconceptions. Building on this foundation, I now turn my focus to misconceptions in chemistry, exploring their prevalence, underlying causes, and strategies for effective remediation.

2.2 Misconceptions in Chemistry

Misconceptions are prevalent across various fields of study, ranging from science to social sciences, often arising from a lack of knowledge or a misunderstanding of fundamental concepts.[47]

In biology, students frequently misunderstand evolution, believing that organisms develop traits because they need them, and struggle with ecological and cellular concepts, such as food webs and diffusion.[48, 49] Similarly, physics misconceptions, including the belief that force is needed to sustain motion, and that electric current is "used up" in circuits, have been widely documented through assessments like the Force Concept Inventory.[50, 51] Studies in psychology have identified persistent misconceptions, such as the belief that people use only 10% of their brains or that schizophrenia involves split personalities.[52, 53]

As a scientific discipline, chemistry is also rife with misconceptions, which are prevalent across nearly all topics, including atomic structure, chemical bonding, reaction mechanisms, acids and bases, thermodynamics, organic chemistry, and nuclear chemistry. A more structured focus on chemistry misconceptions specifically emerged in the 1970s and 1980s.

In 1989, Peterson et al. developed the Covalent Bonding and Structure Diagnostic Instrument, a two-tier diagnostic test designed to assess the understanding of covalent bonding and structure among 243 secondary students (159 Year 11 and 84 Year 12).[54] The study identified several misconceptions, such as the belief that “bond polarity determines the shape of a molecule” (23% of Year 11 students, 27% of Year 12 students). However, it did not explore the differences in performance between Year 11 and Year 12 students or examine the underlying reasons for these differences.

Later in 1992, Griffiths and Preston designed a semi-structured interview to assess Grade-12 students' understanding of atoms and molecules.[55] In addition to identifying 52 misconceptions, they examined how these misconceptions varied among students who differed in academic ability and level of participation in science. They found that while Academic-Science students (N = 10) generally had a better grasp of core concepts compared to Academic-Nonscience (N = 10) and Nonacademic-Nonscience students (N = 10), a statistically significant difference was observed only in Misconceptions 1.3 ("water molecules are composed of two or more solid spheres") and Misconception 9.6 ("collisions may result in a change of atomic size") ($\chi^2 = 6.04$, df = 2, $p < .05$).

Beall administered an open-ended test with three writing questions to his general chemistry students to assess their understanding of thermodynamics.[56] Although the instrument was not formally validated, it still revealed numerous misconceptions. For example, while 73% of students recognized that $\Delta G°$ predicts spontaneity, only 1% explicitly indicated that standard conditions and constant pressure were necessary for the application of $\Delta G°$.

Building on the growing body of research on misconceptions, Garnett et al. published a review paper summarizing the latest findings on students' alternative conceptions across various chemistry topics, including the nature of matter, chemical equations, chemical equilibrium, etc.[57] In their review, chemical equilibrium section drew my attention because many cited studies focused on students from upper secondary and university levels, suggesting that it is a particularly challenging concept. Researchers have also reported that chemical equilibrium is one of the most difficult topics to teach and learn in chemistry, due to its abstract nature, which contributes to the high prevalence of misconceptions.[58, 59] Given these factors, I am especially interested in exploring students' misconceptions about chemical equilibrium.

2.2.1 Educational Research on Misconceptions in Chemical Equilibrium

Research on misconceptions in chemical equilibrium (CE) mainly focuses on three key areas: identifying misconceptions, understanding their causes, and evaluating the effectiveness of remediation strategies. In this section, I will first review common misconceptions identified through different research instruments and develop a CE misconception bank. Then, I will summarize the sources and contributing factors behind these misunderstandings before discussing intervention strategies that have been implemented to address them.

2.2.1.1 Identification of Common Misconceptions in Chemical Equilibrium

Researchers have used multiple-choice diagnostic assessments, interviews, and open-ended tests to identify misconceptions.[60] These misconceptions primarily arise from key principles such as the dynamic nature of equilibrium, the interpretation of the equilibrium constant, the application of Le Châtelier's principle, and the role of catalysts.

Wheeler and Kass developed the Misconception Identification Test (MIT), a 30-item multiple-choice assessment, to evaluate students' understanding of chemical equilibrium.[61] Administered to 99 twelfth-grade students, the test identified six major misconceptions, which are listed in ***Table 2-1***. The results also revealed that 82% of students held at least three misconceptions.

Later, Gorodetsky and Gussarsky became interested in whether different diagnostic methods would affect the effectiveness of identifying students' misconceptions.[62] The authors employed three assessment techniques: a traditional school achievement test, a 26-item multiple-choice diagnostic test, and a free sorting concept mapping task. Students performed better on the school test than on the diagnostic test, which suggests that school assessments may overestimate their understanding. Additionally, students who performed poorly on the diagnostic test also struggled to correctly group related equilibrium concepts. It indicated that their misunderstandings were deeply rooted in their cognitive organization of knowledge. For example, students who misunderstood Feature B (dynamic nature of equilibrium) often grouped equilibrium with "static." Although this paper examines the correlation between different diagnostic methods, it does not explicitly focus on identifying or categorizing specific misconceptions in detail.

Besides using quantitative written tests, researchers have begun considering qualitative approaches to gather more detailed data and better probe students' misconceptions. Hackling and Garnett developed a partially standardized interview instrument to uncover thirty Year 12 students' misconceptions in chemical equilibrium.[63] They used the chemical reaction $NO + Cl_2 \rightleftharpoons NOCl_2 + heat$ as a basis and asked students how the equilibrium would shift if certain changes were applied. Students exhibited misconceptions in almost all propositions, but three major misconceptions stood out, as shown in ***Table 2-1***.

Later, Both Bergquist and Heikkinen[64] and Banerjee[5] adopted a mixed method approach to investigate college students' understanding of CE. Bergquist and Heikkinen first developed a series of equilibrium constant calculation problems based on the reaction $H_2 + I_2 \rightleftharpoons 2HI$ to evaluate students' computational skills.[64] This was followed by think-aloud interviews, where students explained their reasoning while solving equilibrium problems. Their study revealed that while many students correctly applied equilibrium equations, they held fundamental misconceptions. For instance, two-thirds of students failed to distinguish between amount (moles) and concentration (molarity), while others incorrectly assumed that gas volume differs from the container volume. Similarly, Banerjee designed a 20-item paper-pencil achievement test followed by student interviews to gain deeper insights into students' conceptual difficulties.[5] Several misconceptions emerged, including the belief that reactions with very high K or very low K do not have equilibrium (along with others listed in ***Table 2-1***). However, beyond listing these misconceptions, Banerjee didn't present too much quantitative and qualitative data.

More recently, educators have been working to refine diagnostic tests, evolving from two-tier models to more sophisticated three-tier and even four-tier versions for a deeper understanding of student misconceptions.

Özmen developed a 13-item two-tier multiple-choice diagnostic test, the Test to Identify Students' Alternative Conceptions (TISAC) and then administered it to 90 second-semester students enrolled in CHEM 102.[65] The first tier is a multiple-choice question designed to test students' content knowledge, while the second tier requires students to choose the reason for their selected answer in the first tier. Results showed that while 48.8% to 78.8% of students answered the first-tier questions correctly, only 22.2% to 48.8% provided correct responses for both tiers.

Yamtinah et al. also designed a two-tier diagnostic test, but it was computer-based, called the Computerized Two-Tier Multiple-Choice (CTTMC).[66] Unlike Özmen, they coded students' responses as "understand" if both tiers were correct, "misconception" if the first-tier answer was correct but the reasoning was incorrect or indicated a systematic misunderstanding, and "not understand" if both tiers were incorrect or left blank. Results showed that the highest percentage of understanding was observed in high-quality schools (53.8%), while the highest misconception rate was in low-quality schools (32.1%).

However, Siswaningsih and Widasmara argued that traditional two-tier diagnostic tests might inflate misconception rates by failing to differentiate between genuine misunderstandings and random guessing.[67] To address this, they introduced a third tier, where students indicated whether they were sure or unsure about their responses in the first two tiers. The final version of the test consisted of 14 items and was validated by five expert validators. The test demonstrated acceptable reliability, with a Cronbach’s alpha score of 0.759. Analysis of student responses showed that 57.1% of students had misconceptions and believed that the concentration of reactants and products was identical at equilibrium rather than remaining constant.

While three-tier tests help control for guessing, Dewi et al. argued that they still do not verify if students are confident in their reasoning or just in their answer choice.[68] To address this limitation, a four-tier diagnostic test for chemical equilibrium (FTDTCE) was introduced. The first tier presents a multiple-choice question assessing conceptual knowledge, while the second tier asks students to rate their confidence in their selected answer. The third tier requires students to choose the reasoning behind their answer, and the fourth tier assesses their confidence in that reasoning. To validate the test, expert evaluations confirmed content validity (96%) and construct validity (97%), categorizing it as very valid. The test also demonstrated high reliability, with Cronbach's Alpha at 0.848 for the test and 0.834 for confidence levels. Additionally, the authors analyzed the difficulty and discrimination index, finding a good variation among the items. However, this study primarily focused on instrument development. They didn't provide an in-depth discussion of specific student misconceptions in CE.

Table 2-1 Misconceptions in Chemical Equilibrium Reported in the Literature

Subcategories: 1). Dynamic nature of equilibrium; 2). The interpretation of the equilibrium constant; 3) The application of Le Châtelier's principle; 4) The role of catalysts	
Wheeler and Kass[61]	1. Confuse mass with concentration. 2. Misunderstand the difference between reaction rate (how fast a reaction occurs) and reaction extent (how much product is formed). 3. Fail to recognize when the equilibrium constant remains unchanged. 4. Incorrectly apply Le Châtelier's Principle in inappropriate situations (i.e. heterogenous systems). 5. Unable to appreciate that certain substances display a fixed or constant concentration in certain chemical reactions. 6. Overlook all relevant factors that influence the equilibrium state of a chemical system.
Hackling and Garnett[63]	1. The rate of the forward reaction increases with time until equilibrium is reached. 2. A simple arithmetic relationship exists between the concentrations of reactants and products at equilibrium. 3. When equilibrium conditions change, the rate of the favored reaction increases while the other reaction rate decreases
Gage[69]	1. Believe that equilibrium means equal concentrations of reactants and products.

Bergquist & Heikkinen[64]	1. Misinterpret Le Châtelier's Principle, often seeing equilibrium as an oscillating system rather than a dynamic balance. 2. Misunderstand molarity vs. moles when calculating equilibrium concentrations.
Banerjee[5]	1. Assume all provided values in a problem represent equilibrium conditions. 2. Believe reactions with very high K or very low K have no equilibrium 3. Misapply Le Châtelier's Principle to predict rate changes, believing that lowering the temperature of an exothermic reaction increases the forward rate. 4. Think reactions favor lower energy instead of higher entropy. 5. Incorrectly interpretate of the Gibbs free energy equation.
Quílez-Pardo and Solaz-Portoles[58]	1. Assume a 100% conversion in chemical equilibrium, and therefore, misuse the limiting reactant concept. 2. Incorrectly control variables such as volume, pressure, or concentration, leading to faulty equilibrium predictions.
Canpolat et al.[70]	1. When a system at equilibrium is disturbed by increasing the concentration of reactants, the reverse reaction rate will instantaneously decrease. 2. When equilibrium is re-established following an increase in the concentration of reactants, the rates of forward and reverse reactions will be equal to those at the initial equilibrium. 3. When equilibrium is re-established following an increase in temperature, the rates of forward and reverse reactions will be less than at the initial equilibrium. 4. When the system at equilibrium is disturbed by adding the inert gas at constant pressure and temperature, the position of equilibrium will not change.
Özmen[65]	1. At equilibrium, no reaction occurs.

Chemical equilibrium is widely recognized as a highly abstract concept.[59] Beyond uncovering students' misconceptions, scholars have also explored whether teachers themselves still hold misconceptions.

Banerjee designed a 21-item diagnostic test to assess misconceptions in chemical equilibrium among 162 undergraduate chemistry students and 69 secondary-school chemistry teachers, all with more than five years of teaching experience.[71] The study concluded that misconceptions were equally prevalent among both groups. For example, 49% of teachers and 35% of students incorrectly believed that decreasing temperature increases the forward reaction rate of an exothermic reaction, confusing reaction rate with equilibrium position.

Quílez-Pardo and Solaz-Portoles used a comprehensive problem to assess the understanding of Le Châtelier's principle (LCP) among 23 high school and 17 college chemistry teachers.[58] The study aimed to analyze teachers' reasoning strategies, whether they controlled key variables, and if they recognized the limitations of LCP. Results showed that 80% incorrectly predicted equilibrium shifts when a product gas was added at a constant pressure and temperature, 70% misapplied the principle to adding inert gases, and only 10% acknowledged its limitations. Additionally, 85% relied on rote algorithmic problem-solving without analyzing different approaches. These misconceptions suggest that teachers may unintentionally reinforce incorrect problem-solving methods in students.

Cheung used a similar probing question but adopted a think-aloud protocol-based interview approach to examine the understanding of LCP among 12 secondary school chemistry teachers in Hong Kong.[72] Participants were presented with the equilibrium reaction $2N_2 + 3H_2 \rightleftharpoons 2NH_3$ in a reactor with a movable piston at constant temperature and pressure and were asked how the equilibrium would shift if more N_2 was added. The findings revealed two major misconceptions: some teachers set up unsolvable mathematical equations because they failed to consider reaction quotient correctly, while others ignored volume change, mistakenly assuming a fixed system size despite the movable piston. Among the 12 teachers, only one attempted to use K_p instead of K_c to solve the problem. The study argued that the overreliance on LCP in textbooks could foster misconceptions among both students and teachers.

Since most studies identifying misconceptions in chemical equilibrium also analyze their underlying causes, it is necessary to discuss these causes before exploring remediation strategies.

2.2.1.2 Causes of Common Misconceptions in Chemical Equilibrium

According to Soyibo, science misconceptions often stem from various sources including interactions with the socio-physical world prior to formal science instruction, textbooks, reference books, teachers, language and cultural beliefs and practices. These sources also contribute to the misconceptions in chemical equilibrium.[73]

Bergquist & Heikkinen pointed out that vocabulary such as “shift”, “equal”, “stress”, and “balanced” have very different meanings with everyday use.[64] For example, “equal” in daily life normally means two things are exactly the same, which might lead to the misconception that reactants and products are in the same concentration at the equilibrium.

Gussarsky and Gorodetsky asked 309 12th-grade students to produce free associations for "equilibrium" and "chemical equilibrium" before and after formal instruction on chemical equilibrium.[74] Prior to instruction, students associated "equilibrium" with everyday balance concepts like walking, riding, and acrobatics, while "chemical equilibrium" was loosely linked to general chemistry terms such as atoms and molecules. After instruction, students increasingly used specific scientific concepts like Le Châtelier's principle, temperature, and equilibrium constant (K), but also began merging the meanings of "equilibrium" and "chemical equilibrium." In a follow-up problem-solving test, 48% of instructed group and 24% of well-instructed group explicitly described chemical equilibrium as static. The study suggested that teachers should explicitly address the dynamic nature of chemical equilibrium, avoid using "equilibrium" and "chemical equilibrium" interchangeably, and contrast real-life equilibrium examples with chemical equilibrium to prevent misconceptions.

There has also been a broad critique of the overemphasis on the rate approach and Le Châtelier's Principle in chemistry textbooks.[5, 58] Researchers argue that teaching chemical equilibrium primarily through rates can cause students to prioritize kinetic reasoning over thermodynamic principles. For instance, students often mistakenly believe that increasing the temperature in an exothermic reaction will decrease the rate of the forward reaction because equilibrium shifts to the reactant side, as predicted by Le Châtelier's Principle.[71] However, equilibrium laws depend on thermodynamics, not kinetics. Therefore, the thermodynamic approach is likely the most logical way to discuss equilibrium.

In addition to influences from daily life experiences and textbooks, scholars have found that cognitive factors also contribute to the formation of misconceptions in chemical equilibrium. Wheeler and Kass reported a significant correlation between students' cognitive development stages and their chemistry achievement.[61] Students at the concrete operational stage held significantly more misconceptions than those at the formal operational stage ($\chi^2 = 9.3$, $p < .01$). They also found that cognitive reasoning ability, measured by the Piagetian Task Instrument (PTI), was the strongest predictor of correct understanding ($R^2 = 0.375$, $F = 58.2$, $p < .001$).

Recently, Mai et al. reported that students' misconceptions about chemical equilibrium stem from gaps in their conceptual structure.[75] They developed a 24-item questionnaire using a 7-point Likert scale to uncover students' conceptual structures of chemical equilibrium. Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA) revealed low communality values (<0.40) and low factor loadings (<0.40) for key concepts such as Le Châtelier's Principle, reaction quotient (Q), and dynamic equilibrium. These weak statistical relationships suggest that students fail to integrate these fundamental concepts into their conceptual framework, potentially leading to misconceptions.

Understanding the causes of misconceptions is crucial for refining teaching strategies and preventing these misunderstandings from becoming deeply entrenched. It also calls for instructional approaches that not only align with students' cognitive abilities but also foster conceptual change.

2.2.1.3 Remediation Strategies for Misconceptions in Chemical Equilibrium

As I discussed above, addressing misconceptions requires instructional approaches that facilitate conceptual change. Several studies have explored the effectiveness of refutational conceptual change texts in helping students overcome misconceptions about chemical equilibrium.

Canpolat et al. used a quasi-experimental design to test whether a conceptual change approach (using refutational texts, models, and demonstrations) was more effective than traditional instruction in improving students' understanding of chemical equilibrium.[70] 85 undergraduate students were divided into two groups: the experimental group, which received conceptual change-based instruction, and the control group, which followed a lecture-based approach. In their conceptual change texts, they explicitly introduced common misconceptions and then systematically refuted them with scientifically accurate explanations. For example, one misconception addressed was that "the forward reaction must be completed before the reverse reaction starts," which was countered by explaining that in a dynamic equilibrium, both forward and reverse reactions occur simultaneously, and equilibrium is reached when their rates become equal. Results from Chemical Equilibrium Concept Achievement Test (CECAT) showed that the experimental group (70% correct responses) outperformed the control group (51%) after the intervention, and ANCOVA confirmed the difference was statistically significant (F = 66.141, $p < 0.05$). Additionally, science process skills were found to be a significant factor in students' performance (F = 16.227, $p < 0.05$). Furthermore, specific misconceptions were significantly lower in the experimental group compared to the control group after instruction. For instance, the misconception that "equilibrium means equal concentrations of reactants and products" was held by only 7% of students in the experimental group, whereas 55% of students in the control group still retained this incorrect idea. Canpolat et al. also added that conceptual change texts alone may not be enough to fully address misconceptions.[70] Experimental demonstrations and analogies play a crucial role in promoting conceptual change by providing visual and interactive experiences.

Later, both Özmen[76] and Atasoy et al.[77] applied a similar conceptual change approach to 10th-grade students in Turkey and obtained comparable results. With the aid of conceptual change texts, students in the treatment groups demonstrated significantly greater improvement in overcoming misconceptions about chemical equilibrium compared to those in the traditional teaching groups.

Recently, Harza et al. reviewed five general chemistry textbooks and used the reaction $H_2 + I_2 \rightleftharpoons 2HI$ as an example to illustrate how multiple representations may help students learn chemical equilibrium.[78] At the macroscopic level, some textbooks depict the fading purple color of iodine gas to visually demonstrate the dynamic nature of equilibrium. For the submicroscopic level, certain textbooks use atomic models of iodine, hydrogen, and hydrogen iodide molecules to illustrate the continuous molecular interactions towards equilibrium. At the symbolic level, textbooks present the balanced chemical equation along with the mathematical expression for the equilibrium constant to provide a quantitative perspective. Though the authors didn't provide any experimental data, they suggested that educators should integrate varied representations in teaching chemical equilibrium.

As a whole, I aim to present a comprehensive overview of studies on misconceptions in chemical equilibrium. Recognizing and addressing these misconceptions is crucial for enhancing both teaching effectiveness and student learning in this complex domain.

2.3 Graduate Teaching Assistants in the United States

Graduate teaching assistants (GTAs) in the United States play a crucial role in higher education. They often lead discussion sections, facilitate laboratory courses, and even serve as primary instructors, playing a crucial role in bridging the gap between faculty-led instruction and student engagement.[79]

As universities face increasing teaching demands and budgetary constraints, reliance on GTAs as part of the instructional workforce continues to grow.[80] Despite their significance, the training and support available to GTAs remain inconsistent, with many reporting little to no formal preparation for their instructional roles.[81]

Given that undergraduate students expect GTAs to demonstrate both subject-matter expertise and effective pedagogical strategies, substantial research efforts are focused on developing structured GTA training programs to enhance their teaching preparedness.[82, 83] These training programs vary from several-day general orientations to semester-long courses and mainly focus on GTA' pedagogical content knowledge (PCK) and professional development (PD).

For example, Bond-Robinson and Rodriques designed a one-semester GTA training program that included weekly one-hour seminars, coaching sessions, and video-based self-assessments, along with structured formative and summative evaluations.[84] They also used the Instructor Teaching Assessment Tool (ITAT) to measure GTAs' effectiveness in managing labs and teaching chemistry concepts. The assessments showed that 95% of GTAs became effective lab managers. It indicated that the structured training significantly improved teaching skills.

Lang et al. developed an eight-week GTA training course at Purdue University.[85] The training covered 8 sessions including building confidence in the classroom, active learning strategies, meaningful grading, reflective teaching, and classroom management. They used end-of-semester surveys to measure GTAs' perceptions of course effectiveness, engagement, and the applicability of teaching methods. They found that 70% of new GTAs valued peer discussions, 67% benefited from roundtable activities, and 55% found active learning sessions particularly useful. The peer observation series, where GTAs observed and were observed by peers and mentors, was rated highly, with 55% identifying it as a "great help" to their teaching practice.

Besides enhancing GTAs' teaching abilities, studies also examine undergraduate students' perceptions of GTAs, as well as GTAs' reflections on their roles and responsibilities. Kendall and Schussler investigated undergraduate students' perceptions of GTAs versus professors in classroom settings.[86] They conducted an online survey using validated instruments to measure perceptions related to instructional characteristics, classroom environment, and interpersonal relationships. The results showed that undergraduates viewed professors as more knowledgeable, structured, and respected but also more distant and formal, while GTAs were seen as more engaging, approachable, and relatable but also less confident and experienced. The study suggests that GTA professional development should aim to retain their engaging qualities while improving their perceived authority and confidence in the classroom.

Cho et al. explored GTAs' teaching concerns using a structured online survey distributed to 228 GTAs from various disciplines at a large southwestern university in the USA.[87] Through Exploratory Factor Analysis (EFA), five key teaching concerns were identified: class control, external evaluation, task, impact, and role/time/communication. Results showed that GTAs were most concerned about role/time/communication ($M = 4.03$, $SD = 0.83$) and impact ($M = 3.96$, $SD = 0.71$) issues. It means that training programs should enhance GTAs' confidence and teaching skills to shift their concerns from "deficiency" (self and task worries) to "growth" (student impact), while also providing support for role balancing and time management, which were among the highest concerns reported.

2.4 Relevance of This Study

2.4.1 Research Gap and Study Rationale

Chemical equilibrium is widely recognized as one of the most challenging topics in chemistry for students to understand. As reviewed in the previous section, misconceptions about chemical equilibrium are not only prevalent among students but also among teachers. It means that these misunderstandings persist even at advanced levels of education.[64] However, despite extensive research on misconceptions in chemical equilibrium, no studies have specifically examined whether graduate teaching assistants (GTAs), who play a crucial role in undergraduate education, hold similar misconceptions.

GTAs interact frequently with students during recitations, labs, and office hours, making them influential figures in students' learning experiences.[82] Research also indicates that both course instructors and TAs significantly shape students' perceptions of chemistry.[88] If GTAs themselves hold misconceptions about chemical equilibrium, they may unintentionally reinforce or introduce misunderstandings in their students. Therefore, identifying and addressing these misconceptions is therefore not just a matter of improving teaching assistant training but a broader issue of enhancing student learning outcomes in chemistry.

While existing research on GTAs primarily focuses on their pedagogical content knowledge (PCK) and how departmental training programs can better prepare them for teaching responsibilities, little attention has been given to the specific content knowledge GTAs possess. Additionally, while GTA training programs aim to improve teaching effectiveness, many GTAs view these programs as an additional burden on top of their already demanding graduate studies.[89] Studies suggest that GTAs prefer training that is concise, directly applicable, and tailored to their immediate teaching responsibilities rather than generalized teaching preparation.[90]

2.4.2 Purpose of This Study

To address this gap, this study aims to develop an instrument to diagnose misconceptions in chemical equilibrium among GTAs. By identifying whether GTAs hold misconceptions similar to those observed in students and teachers, this study will provide insights into potential areas for improvement in GTA training.

Furthermore, beyond just diagnosing misconceptions, this study seeks to develop a targeted mini lecture to address common misconceptions in chemical equilibrium. The goal is to create a resource that not only corrects misunderstandings but also serves as a practical, time-efficient teaching aid that GTAs can use to prepare for their instructional duties. Given the significant workload GTAs face, it is essential that any intervention be both effective and manageable within their existing responsibilities. To evaluate the usefulness of this mini-lecture, GTAs will be interviewed to gather feedback on its clarity, effectiveness, and applicability to their teaching preparation.

Chapter 3 Methodology

Through my review of the literature, I have seen how misconceptions in chemical equilibrium persist across different educational levels. While much research has focused on students and teachers, little attention has been given to GTAs. This gap led me to investigate GTAs' conceptual understanding of chemical equilibrium, assess the effectiveness of a mini-lecture designed to correct misconceptions, and examine how GTAs perceive its usefulness for their teaching preparation. Based on these objectives, I formulated the following research questions:

1. What misconceptions about chemical equilibrium do first-year graduate teaching assistants (GTAs) in CHEM 1315 (General Chemistry 1) hold before teaching the topic in the "Reversible Reactions" laboratory session?
2. What misconceptions do GTAs demonstrate while teaching chemical equilibrium during the "Reversible Reactions" laboratory session?
3. How do GTAs' misconceptions change after attending the mini-lecture?
4. What are GTAs' perceptions of the mini-lecture, and what additional support do they believe would enhance their teaching as GTAs?

To address these research questions, this chapter is guided by three key considerations. First, what research methodologies and methods are most appropriate for this study? Second, how can these methodologies and methods be justified? Third, how will the study be conducted to address the research questions effectively? By answering these questions, this chapter provides a detailed account of the research design, data collection strategies, and analytical procedures used in this study.

3.1 Research Philosophy

Research philosophy is the underlying belief system that influences how I, as a researcher, see the world and engage with it. It helps me think about how I interpret the nature of reality and knowledge, guiding the choices I make in research design, practice, and reporting. Reflecting on my philosophical stance is crucial, as it establishes the foundational assumptions that underpin this study and ensures coherence in how the research is conducted and presented.

Different researchers offer various structures for discussing philosophical foundations. Terms such as approaches, paradigms, theoretical perspectives, methodology, and methods are often organized differently by various authors.[91] Creswell and Clark define a paradigm as a worldview including ontology and epistemology, which then guides the selection of specific methodologies and methods for data collection (see ***Figure 3-1***).[92]

My approach aligns with Creswell's model, emphasizing ontology and epistemology as foundational components to provide a comprehensive foundation for this study.

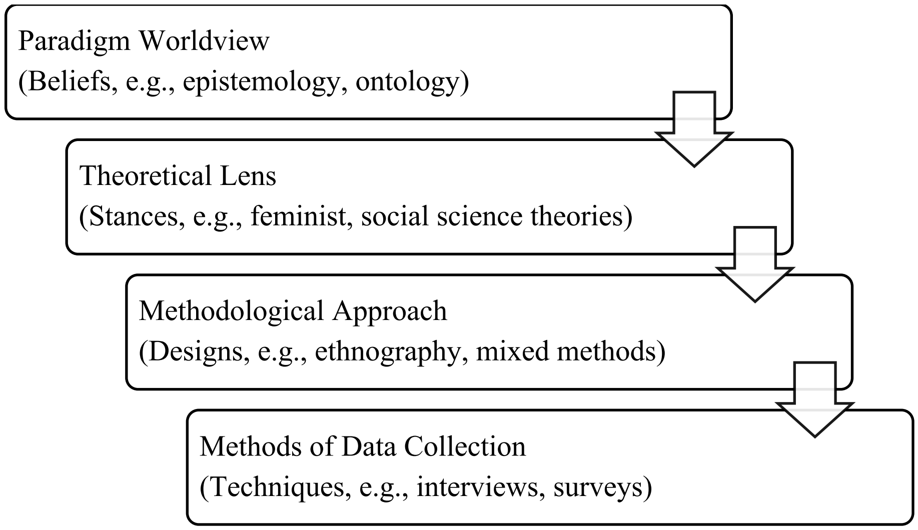

Figure 3-1 Creswell and Clark's model of Research Philosophy

3.1.1 Ontological and Epistemological Stances

A philosophical stance usually means thinking about two main things: ontology and epistemology.[93] Ontology refers to beliefs about the nature of reality and how we perceive and understand the existence of social phenomena.[94] It leads us to ask questions like: "What is reality?" and "Is there one objective reality, or is reality shaped by people's experiences and perceptions?" While ontology reflects on the nature of reality, epistemology focuses on the nature of knowledge and how it is acquired.[95] It involves considering questions such as: "How is knowledge acquired?" "Can knowledge be objectively discovered and measured?" or "Is knowledge created through interpretation and social interaction?" Understanding these questions is crucial for shaping how knowledge is approached and validated in research.

3.1.1.1 Ontological Stances

In social science research, common ontological positions include objectivism, constructivism, realism. Objectivism asserts that reality exists independently of human perception or beliefs. Social phenomena have an objective existence, separate from the individuals who observe or engage with them. On the other hand, constructivism suggests that reality is shaped by people's experiences, perceptions, and interactions. These two ideas are completely opposite, as if they're the only ways to understand the social world. But realism offers a kind of middle ground. Realism agrees with objectivism that reality exists independently of human thought but also acknowledges that some aspects of reality may be unobservable and interpreted through experience.[94]

Besides these three stances, pragmatism, however, takes a more flexible approach. It doesn't focus on whether reality is fixed or independent. Instead, it cares about what works in practice. For pragmatists, knowledge and truth are judged by how useful they are in solving problems. Pragmatism is about finding practical solutions and focusing on what is effective in a given context, rather than worrying about the deeper nature of reality.[96]

In this study, I adopt a pragmatic ontological stance. My primary concern is to explore GTAs' misconceptions about chemical equilibrium, understand how these misconceptions influence their teaching practices, and examine how practical and effective interventions, such as the development of a targeted mini-lecture, can be used to address them. Pragmatism aligns with the applied nature of this research, as it values approaches that are useful, efficient, and contextually relevant for improving teaching and learning experiences.

3.1.1.2 Epistemological Stances

There is a range of epistemological stances prevalent in social science research, including positivism, interpretivism, constructionism, social constructionism, pragmatism, etc. Positivism holds that knowledge exists independently of human perception and can be measured objectively through scientific observation and empirical data.[97] In contrast, interpretivism suggests that knowledge is constructed trough human interpretation. It emphasizes the subjective nature of human experience.[98]

Constructionism argues that knowledge cannot be described as simply "objective" or "subjective." Instead, it is constructed through social processes and interactions. According to this view, there is no objective truth waiting to be discovered. Meaning arises from our engagement with the world, and different individuals may construct meaning differently, even when experiencing the same phenomenon.[99] Social constructionism extends this idea by emphasizing the role of culture in shaping knowledge.[99] According to Geertz, culture is not just a product of human thought but a framework for making sense of the world. In this view, culture shapes how people interpret and construct knowledge.[100]

Pragmatism, in contrast, focuses on practical usefulness. It argues that knowledge is true if it works in practice. For pragmatists, ideas and theories are evaluated based on their usefulness and effectiveness in addressing real-world problems.[97]

In this study, I adopt a pragmatic epistemological stance. My primary concern is not whether knowledge about chemical equilibrium exists as an objective truth or is socially constructed. Instead, I focus on finding solutions that can improve GTAs' teaching and learning outcomes. Moreover, the pragmatic stance allows for flexibility in selecting research methods while ensuring that the chosen approaches focus on real-world outcomes.

3.1.2 Theoretical Framework – Constructivist Learning Theory

The term "constructivism" is used in both epistemology and learning theory to explain how individuals acquire and develop knowledge.[101] Constructivist learning theory suggests that learners actively construct their understanding of the world by engaging with experiences and reflecting on them. Rather than passively absorbing information, learning is an active and contextualized process. More importantly, constructivism asserts that learners are not blank slates but bring prior knowledge that influences how they interpret new information.[4] Several theorists have contributed to the development of constructivist theory, such as Jean Piaget and Lev Vygotsky. Piaget's work focused on cognitive development while Vygotsky emphasized the role of social interactions and cultural context in shaping learning.[102]

In educational psychology, constructivism is closely associated with Piaget's theory of cognitive development, which describes how children's thinking and reasoning evolve through sequential stages. According to Piaget, intellectual development occurs through four major stages: the sensorimotor, preoperational, concrete operational, and formal operational stages.[103] In the concrete operational stage (around ages 7 to 12), children develop logical reasoning related to concrete objects and events. Then, in the formal operational stage (around age 12 and older), students start to develop abstract and hypothetical thinking. Learners begin to formulate and test hypotheses and reason about abstract concepts beyond immediate, tangible experiences. This link between developmental stages and concept understanding implies that educational instruction should be designed to help students progress from concrete reasoning to higher-order, abstract thinking, which is essential for understanding scientific concepts.

According to Piaget's intellectual model, learning occurs through two key processes: assimilation and accommodation. Assimilation occurs when learners encounter new information that fits into their existing mental frameworks or schemas without altering them.[104] While assimilation allows learners to quickly process familiar information, it can also reinforce misconceptions if the initial schema is flawed. In contrast, accommodation occurs when new information cannot fit into existing schemas, prompting learners to modify or develop new ones. This process is often triggered by disequilibrium, the discomfort learners feel when they encounter information that conflicts with their current understanding. Disequilibrium is a critical driver of cognitive growth because it motivates learners to adjust their thinking to resolve inconsistencies. However, learners do not always readily accept this discomfort. They may resist accommodation by attempting to force new, conflicting information into existing frameworks, even if it results in misconceptions. Therefore, for accommodation to occur, learners must first acknowledge the inconsistency and experience dissatisfaction with their current understanding.

In educational settings, it is essential for instructors to first elicit learners' prior knowledge to identify potential misconceptions. Once these are recognized, teachers should introduce activities or discussions that create cognitive conflict, encouraging learners to question their assumptions. This approach helps foster deeper learning and supports the development of more accurate scientific understanding.

3.1.3 Research Methodology – Mixed Methods Research Design

Mixed methods design is an approach to research that integrates both quantitative and qualitative methodologies within a single study.[92] This design appreciates the limitations and strengths of each method and seeks to combine them in a way that provides a more comprehensive understanding of research problems. Quantitative research often yields generalizable, statistically significant results through numerical data, while qualitative research offers rich contextual data. By integrating these two approaches, mixed methods design enables researchers to explore research questions from multiple angles.

In mixed methods research, three foundational designs are commonly utilized to integrate qualitative and quantitative approaches: the convergent design, the explanatory sequential design, and the exploratory sequential design. In the convergent design, researchers collect quantitative and qualitative data at the same time but analyze them separately. The findings are then compared, contrasted, or combined to determine if the two databases yield similar or dissimilar results. This design is ideal when researchers equally prioritize both types.

The explanatory sequential design (see ***Figure 3-2***) begins with the collection and analysis of quantitative data, then followed by qualitative data collection to explain or elaborate on the initial results. This design is often chosen when quantitative findings require further interpretation or when researchers aim to understand the underlying reasons for statistical trends.

Lastly, the exploratory sequential design operates in the reverse order. It starts with qualitative data collection to explore a phenomenon in-depth, followed by quantitative data collection to test or generalize the initial qualitative insights. This approach is particularly useful when developing new instruments or frameworks based on initial qualitative findings. Each design offers a distinct pathway for integrating data, and the choice depends on the research questions, objectives, and the role each type of data plays in the study.

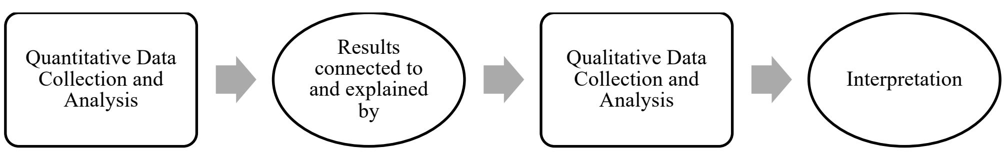

Figure 3-2 General Diagram of Explanatory Sequential Design

Creswell also proposes several complex mixed methods designs, such as the experimental design, the social justice design, and the multistage evaluation design.[92, 105] The experimental mixed methods design integrates a basic mixed methods approach within an experimental framework (see ***Figure 3-3***). In this design, qualitative data can be collected at various stages: before the experiment to help design the intervention (exploratory sequential), during the experiment to capture participants' real-time experiences (convergent), or after the experiment to explain and elaborate on the quantitative results (explanatory sequential). While quantitative data primarily assesses the effectiveness of the intervention, qualitative data explores how participants perceive and engage with the process. In this design, the primary focus is often on quantitative results, with qualitative data serving a supportive and explanatory role.

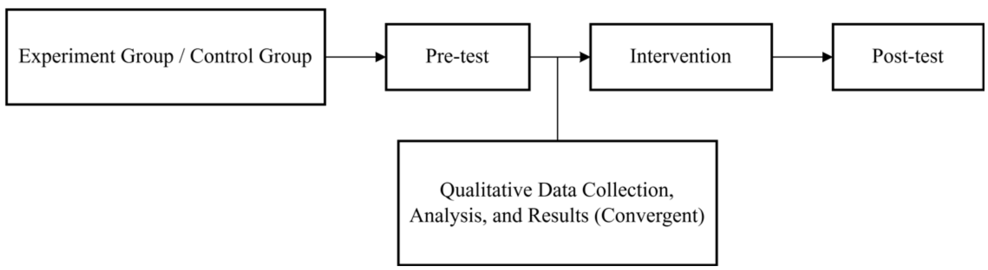

Figure 3-3 General Diagram of Experimental Mixed Methods Design (Adapted from Creswell [105])

My study adopts a sequential explanatory mixed methods design with an embedded qualitative component. The primary phase involves quantitative data collection through pre- and post-diagnostic tests to measure GTAs' misconceptions about chemical equilibrium. Qualitative observations are conducted to explore how these misconceptions may be conveyed during teaching. An embedded qualitative phase involves interviews with GTAs to gather their perceptions of the diagnostic test’s utility for potential application in TA training programs. This design ensures both an understanding of misconceptions and an evaluation of the diagnostic tool's practical relevance. My study also shares features with an experimental mixed methods design due to its quasi-experimental structure involving pre- and post-tests and an intervention. However, Creswell and Clark suggest that researchers who adopt an experimental mixed methods design often align with a post-positivist worldview.[92] Since I hold a pragmatic worldview, which values practical solutions and methodological flexibility, I focus more on the sequential explanatory design. This approach better reflects the study's aim to not only measure misconceptions but also explore their practical implications for TA training.

3.2 Research Methods

3.2.1 Setting

The data were collected at a public, four-year university with high research activity. The Department of Chemistry and Biochemistry at this university offers a one-year general chemistry course sequence for undergraduate students: CHEM 1315 (General Chemistry 1) and CHEM 1415 (General Chemistry 2). For the sake of clarity, CHEM 1315 will be referred to as CHEM 1, and CHEM 1415 as CHEM 2. Both CHEM 1 and CHEM 2 are typically required for students pursuing STEM or pre-professional majors (e.g., medicine, dentistry, pharmacy). CHEM 1 is also commonly required for engineering and allied health majors (e.g., nursing). Each course consists of three components: lecture, laboratory, and recitation.

- Lecture: Lectures are conducted by faculty professors and are held either three times a week for 50 minutes or twice a week for 75 minutes. Both courses include three midterm exams, scheduled approximately every four weeks, and one comprehensive final exam. CHEM 1 covers foundational topics such as measurement, atomic theory, electron configuration, periodicity, chemical reactivity, energetics, stoichiometry, gas laws, changes in state, bonding, and molecular structure. CHEM 2 includes more advanced topics such as thermochemistry, equilibrium, thermodynamics, acid-base properties, kinetics, and electrochemistry.

- Laboratory and Recitation: Teaching assistants (TAs) in CHEM 1 and CHEM 2 are responsible for leading both recitation and laboratory activities. Each section enrolls up to 24 students and meets once a week. Recitation classes are scheduled for 50 minutes, while laboratory sessions last for 3 hours. For recitations, TAs prepare a 10-minute presentation and a worksheet with approximately 10 questions to help students review lecture material. To assist with this, the general chemistry team provides TAs with question banks for each lecture unit, allowing them to select relevant questions for the worksheets. During laboratory sessions, TAs provide brief explanations of the chemical reactions involved in each experiment and demonstrate key laboratory techniques, such as how to use a Büchner funnel. Throughout the session, TAs circulate the room to address student questions and ensure proper execution of experiments. A total of 10 experiments are conducted over the semester. Both recitation and laboratory activities are designed to align closely with lecture content, offering students complementary practice and reinforcement of key concepts.

CHEM 1 typically enrolls more students in the fall semester (approximately 1,000) than in the spring (around 800), as incoming first-year students from high school begin their chemistry sequence. In the spring semester, enrollment in CHEM 2 increases as students who completed CHEM 1 in the fall advance to the next course in the sequence. Since Fall 2021, enrollment trends have remained consistent (see ***Table 3-1***).

In Spring 2023, CHEM 1 had an enrollment of 824 students across four lecture sections, while CHEM 2 enrolled 430 students in three sections. In Fall 2023, CHEM 1 saw an increase to 970 students across six sections, whereas CHEM 2 enrollment decreased to 212 students in one section.

Table 3-1 Enrollment Numbers for CHEM 1315 and CHEM 1415 (Fall 2021 – Spring 2024)

	CHEM 1315	CHEM 1415
Fall 2021	1005	328
Fall 2022	998	205
Fall 2023	970	212
Spring 2022	768	459
Spring 2023	824	430
Spring 2024	894	400

3.2.2 Sample Population

Graduate teaching assistants (GTAs) in the Department of Chemistry and Biochemistry play a crucial role in undergraduate education, particularly in general chemistry courses. The GTA cohort primarily consists of doctoral students enrolled in the department's PhD program.

The teaching assistant team for CHEM 1 and CHEM 2 typically consists of approximately 40 graduate students, most of whom are in their first or second year of graduate study. Senior graduate students (third year and beyond) are usually assigned to teach advanced chemistry courses (e.g., Organic Chemistry, Analytical Chemistry) or serve as research assistants in their principal investigators' laboratories. Because CHEM 1 and CHEM 2 have high enrollment and serve as gateway courses for many students, the misconceptions held by general chemistry TAs can significantly impact a large number of undergraduates. These students, often in their first or second year, typically have a weaker foundation in chemistry, making them more susceptible to being influenced by their TAs' understanding of the subject. Given the potential for widespread influence, I firstly narrowed my target sample to general chemistry GTAs rather than all graduate TAs.

As mentioned earlier, CHEM 1 and CHEM 2 are sequential courses. CHEM 1 wraps up with enthalpy change calculations in chemical reactions, while CHEM 2 starts with thermodynamics. Based on the planned learning objectives for these courses, chemical equilibrium is introduced toward the end of CHEM 1, around Exam 3 (approximately one month before the final exam), but in the first two weeks of CHEM 2. The focus of chemical equilibrium instruction also differs between the courses: CHEM 1 covers fundamental concepts such as Le Châtelier's principle and the general behavior of reversible reactions, whereas CHEM 2 mainly focuses on equilibrium constant calculations. Additionally, CHEM 1 includes a laboratory experiment specifically designed for chemical equilibrium (the ninth lab out of ten), titled "Reversible Reactions." In this experiment, TAs are expected to introduce the concept of chemical equilibrium to students. In contrast, CHEM 2 does not have a designated laboratory activity on this topic. Considering these factors, I decided to focus solely on GTAs in CHEM 1, as they play a direct role in introducing chemical equilibrium to students in laboratory settings.

Within CHEM 1, GTAs can be categorized into two groups: new GTAs and experienced GTAs. New GTAs are incoming doctoral students, while experienced TAs have taught CHEM 1 for multiple semesters. Initially, my goal was to examine misconceptions among newly admitted TAs who had not yet had the opportunity to refine their knowledge through teaching. However, since data collection took place in Spring 2023, most of the participating TAs had already taught CHEM 1 for one semester in Fall 2022. Despite this, these TAs were still in their first year of the PhD program, making them relatively new instructors with limited prior teaching experience. Therefore, to ensure that my findings capture the most unfiltered misconceptions, I ultimately decided to focus exclusively on first-year doctoral TAs, as their misconceptions were likely to be less influenced by extensive teaching exposure while still representing the early stages of their instructional development.

3.2.3 Recruitment and Selection Procedure

In Spring 2023, 17 new doctoral students entered the department, while in Fall 2023, there were 20 incoming doctoral students. In Spring 2023, CHEM 1 had a total of 38 recitation and laboratory sections. These sections were led by 14 first-year doctoral students, 5 upper-year doctoral students, and 2 undergraduate students. In Fall 2023, the number of CHEM 1 sections increased to 45, with teaching assignments distributed among 14 first-year doctoral students, 9 upper-year doctoral students and 3 undergraduate students.

The selection of participants for this study was guided by purposeful sampling, specifically criterion sampling. Purposeful sampling is a sampling technique that qualitative researchers use to recruit participants who can provide in-depth and detailed information about the phenomenon under investigation.[106] However, Palinkas et al. argue that purposeful sampling is also a valuable strategy in mixed-methods research, as it helps balance the depth and breadth of data collection.[107] Criterion sampling, a subcategory of purposeful sampling, involves selecting cases that meet specific predefined criteria.[106] For this study, participants were selected based on the following criteria: (1) they must be first-year doctoral students, and (2) they must have served as CHEM 1 GTAs during Spring 2023 or Fall 2023. This method ensured that only participants who fit the study's focus were included.

Additionally, the study's sampling approach also aligns with convenience sampling, as participant selection was limited to the available pool of first-year TAs within the department during the specified semesters. The accessibility of these participants made recruitment feasible while maintaining alignment with the study's objective of exploring misconceptions in relatively new instructors. By combining criterion sampling and convenience sampling, I was able to recruit participants who best fit the study's objectives while also working within practical constraints of accessibility and feasibility.

3.2.4 Development of the Chemical Equilibrium Diagnostic Test

When planning the diagnostic test for this study, I first considered the role of GTAs in CHEM 1. As mentioned earlier, GTAs are responsible for explaining experiments at the beginning of each laboratory session. Therefore, the test needed to assess their conceptual understanding of chemical equilibrium. Additionally, given that GTAs are faced with heavy teaching and research duties, the test needed to be time-efficient to minimize their workload. Since no reimbursement was planned for participation, it was important to ensure that the test could be completed within a reasonable time frame. With these factors in mind, I wanted the diagnostic test for this study to meet the following criteria: (1) effectively assess GTAs' understanding of CE, (2) be concise and require minimal time to complete, and (3) be appropriately challenging for GTAs at their academic level.

Several diagnostic tests on CE have been developed in previous studies. For example, Wheeler and Kass (1978) designed the Misconception Identification Test (MIT), a 30-item multiple-choice test,[61] while Gorodetsky and Gussarsky created a 26-item multiple-choice diagnostic test.[62] However, I was unable to find the original versions of these tests in the supporting information. Hackling and Garnett developed an interview-based test to assess students' understanding of CE across several key aspects: (1) approach to equilibrium, (2) characteristics of chemical equilibrium, and (3) changes in equilibrium conditions, including effects on concentrations, initial effects on reaction rates, reaction rates when equilibrium is re-established, equilibrium constants, and the role of catalysts in equilibrium.[63] Additionally, Bergquist and Heikkinen introduced a series of equilibrium constant calculation problems to evaluate students' computational skills.[64] Later, Özmen developed the Test to Identify Students' Alternative Conceptions (TISAC), covering topics such as the approach to equilibrium, application of Le Châtelier's principle, constancy of the equilibrium constant, heterogeneous equilibrium, and the effect of catalysts.[65]

While reviewing these instruments, I found that they primarily targeted undergraduate or high school students, making the questions slightly simplistic for GTAs. As a result, I turned to studies which examined teachers' misconceptions in CE.

Banerjee designed a 21-item diagnostic test to assess secondary-school chemistry teachers' understanding of CE, focusing on: (a) applying Le Châtelier's principle to predict equilibrium conditions, (b) relating reaction rates to equilibrium, (c) applying equilibrium principles to real-world contexts, and (d) understanding equilibrium in acid-base and ionic solutions.[71] Additional studies by Cheung used a gaseous reversible reaction to assess whether teachers could predict equilibrium shifts when reactant gas was added at constant temperature and pressure.[72, 108]

After reviewing these existing instruments, I found that Banerjee's diagnostic test aligned best with the content covered in CHEM 1 and provided an appropriate level of difficulty for doctoral students. Therefore, I selected his test as the foundation for further adaptation and development in this study.

Next, I reviewed the CHEM 1 learning objectives and identified only one objective related to chemical equilibrium: "*9.6. Explain Reversible Reactions [Readings: 15.1, 15.2, 15.6]*." To ensure alignment with course content, I then carefully examined lecture slides, textbook chapters 15.1, 15.2, and 15.6, as well as student homework assignments. I found that the CHEM 1 curriculum primarily focuses on the dynamic nature of chemical equilibrium, equilibrium constants, and Le Châtelier's principle. Regarding equilibrium constants, CHEM 1 students are only expected to understand that K is temperature-dependent, and that a large K favors products while a small K favors reactants. For Le Châtelier's principle, students are required to qualitatively determine the shift direction of equilibrium in response to changes in conditions. However, an analysis of student homework and exam questions revealed that they were assessed only on Le Châtelier's principle. Given this emphasis, I decided to prioritize GTAs' understanding of Le Châtelier's principle in my diagnostic test adaptation. Consequently, when adapting Banerjee's test, I retained only the first two categories: (a) applying Le Châtelier's principle to predict equilibrium conditions and (b) relating reaction rates to equilibrium. This adaptation ensured that the diagnostic test closely aligned with the CHEM 1 curriculum while appropriately challenging doctoral students at their level of expertise.

The first version of the Chemical Equilibrium Diagnostic Test (CEDT) was built around a reversible reaction and consists of five multiple-choice subquestions, as shown in ***Table 3-2***.

Table 3-2 Items Adapted from Banerjee's Diagnostic Test in the CEDT

1. Consider an equilibrium mixture of CO, Cl_2, $COCl_2$ at 200 °C and 1 atmosphere pressure present in chemical equilibrium:

$$CO\ (g) + Cl_2\ (g) \rightleftharpoons COCl_2\ (g) + heat$$

Responses for questions (1) to (5) are to be given as: A: greater than the initial amount; B: less than initial amount; C: same as the first equilibrium; D: data insufficient for conclusion

(1) The mixture is cooled to 150 °C, keeping the volume constant. When the system returns to a new equilibrium,
  (a) the mass of $COCl_2$ present will be...
  (b) the rate at which $COCl_2$ is being formed will be...
  (c) the equilibrium constant will be…

(2) The volume of the system is halved by increasing pressure at constant temperature. When the system returns to a new equilibrium,
  (a) the mass of $COCl_2$ present will be...
  (b) the concentration of $COCl_2$ present will be...
  (c) the mass of CO present will be...
  (d) the concentration of CO present will be...

(3) Some Cl_2 is removed from the system, the volume and the temperature being kept constant. When the system returns to a new equilibrium,
  (a) the mass of CO will be…
  (b) the equilibrium constant will be...
  (c) the rate at which CO is being formed will be...

(4) 1 mole $COCl_2$, and 0.01 mole Cl_2 is added to the system at constant volume and temperature. When the system returns to another equilibrium, how does the mass of CO change? Include the rational.

(5) When temperature is increased, the rate of the forward reaction will
  (a) Increase
  (b) Decrease
  (c) Unchanged
  (d) Data insufficient for conclusion

However, Quílez argued that chemical equilibrium is an abstract concept prone to misconceptions because it requires an understanding of multiple subordinate concepts, such as reaction rate, mass, moles, and physical principles like pressure.[109] More recently, Jusniar et al. investigated whether misconceptions about the rate of reaction (RR) contribute to misconceptions in chemical equilibrium (CE) and found a significant correlation ($r = 0.39$, $p = .001$).[110] Their study identified several RR misconceptions that affected CE, including misunderstandings of the mathematical expression of reaction rate, changes in reaction rate over time, the effect of temperature, and the role of catalysts in activation energy. Since these concepts are prerequisites for understanding CE, I considered their relevance to the diagnostic test.

Upon reviewing the CHEM 1 learning objectives, I noticed that students are introduced to chemical equilibrium without prior instruction on rate of reaction. However, since an understanding of equilibrium conditions requires knowledge of the forward and reverse reaction rates, I decided that assessing GTAs' prior knowledge of RR would be beneficial. Additionally, since the test employed a one-tier multiple-choice format, including RR-related questions would help me analyze GTAs' misconceptions in CE.

Therefore, I adapted four questions from Jusniar et al.'s study, as shown in ***Table 3-3***. While Jusniar originally used a three-tier multiple-choice format, I opted to modify these questions into an open-ended format. Given that GTAs primarily explain basic CE concepts verbally, such as forward and reverse reaction rates, open-ended questions better align with their instructional role by assessing their ability to articulate their understanding.

Table 3-3 Items Adapted from Jusniar et al. in the CEDT

1. Consider a reaction where chemicals 'A' and 'B' react to form 'C', $A + B \rightarrow C$. Explain in your own words what you understand by the term "rate of reaction."
2. The $Mg\ (s) + 2HCl\ (aq) \rightarrow MgCl_2\ (aq) + H_2\ (g)$ reaction experiment was carried out. An increase in temperature can cause an increase in the reaction rate. The proper explanation for this is…
3. Explain how catalysts affect the rate of reactions.
4. At a temperature of 25 °C a reaction occurs as follows: $Na_2S_2O_3\ (aq) + 2HCl\ (g) \rightarrow 2NaCl\ (aq) +\ H_2O\ (l) + SO_2\ (g) + S\ (s)$ If the rate of formation of sulfur is 2 mol/min, then... (A) the rate of reduction of sodium thiosulfate is 1 mol/ min (B) the rate of formation of sodium chloride is 4 mol/min (C) the rate of formation of sulfur dioxide is 1 mol/min (D) the rate of formation of sodium chloride is 2 mol/min Based on the information above, can you determine the rate of the reaction? If yes, explain how:
If no, explain why:

Therefore, by combining these two parts, the first full draft of the CEDT consists of two sections: the first assessing prerequisite knowledge on reaction rates and the second focusing on key concepts in chemical equilibrium. This structure ensures a comprehensive evaluation of GTAs' conceptual understanding while also identifying any underlying misconceptions that may influence their explanations in the classroom.

Face validity refers to the extent to which a test appears, on the surface, to measure the concept or construct it is intended to assess. It is typically evaluated based on the subjective judgment of researchers or experts.[111] After reviewing the initial version of the test, my principal investigator and I decided to eliminate the question on the effects of catalysts on reaction rate, as catalysts are not covered in the CHEM 1 curriculum. Additionally, we removed question (3c), "the rate at which CO is being formed will be..." since CHEM 1 only requires students to understand the initial effects on reaction rates, rather than how the rate changes once a new equilibrium is established. Later, I distributed the test to 28 CHEM 1 undergraduate students to gather feedback on the clarity of the wording. Students generally reported that the questions were easy to understand, even if they were unsure how to answer them correctly.

The content validity of the CEDT was evaluated by consulting 6 experts (2 faculty chemists and 2 high school chemistry teachers and 2 doctorate holders) to rate the test with respect to: (a) the representativeness of the items from the total pool of possible items for the content covered; and (b) the readability and clarity of the items.[112] The scale content validity index (S-CVI) for the instrument was reported as 0.97, indicating good content validity.

3.2.5 Mini-Lecture Development

As discussed in the literature review and theoretical framework, presenting students with refutational texts can induce cognitive disequilibrium, which in turn promotes the correction of misconceptions. Therefore, I structured my mini-lecture to explicitly confront and clarify possible misconceptions in CE. Additionally, since I intend for the mini-lecture to serve as a review resource for GTAs as they prepare for teaching in the future, I aimed to keep it concise and efficient for their use.

Drawing on studies such as Canpolat et al.,[70] the mini-lecture is structured around three interactive multiple-choice questions. To ensure consistent message delivery across different GTA cohorts over two semesters, I included speaker notes at the bottom of each slide. This helps maintain uniformity in instruction, ensuring that every group receives the same key information and explanations. With practice, the mini-lecture is expected to last approximately 15 minutes. ***Table 3-4*** showed all the slides presented to GTAs.

Table 3-4 Slides Presented in Mini-Lecture

Slide 1: 1. Which of the following can represent the rate of the chemical reaction? $2NO\ (g) + Cl_2\ (g) \rightleftharpoons 2NOCl\ (g)$? a. $\Delta[NO]/\Delta t$ b. $-\Delta[NO]/2\Delta t$ c. $\Delta[Cl_2]/\Delta t$ d. $-\Delta[NOCl]/\Delta t$ e. $\Delta[NOCl]/2\Delta t$ f. None of above

Notes: According to IUPAC's definition, the rate of a chemical reaction is expressed as the change in concentration of a reactant or product per unit time. For a general reaction of the form:

$$aA + bB \rightleftharpoons cC + dD$$

the reaction rate can be written as:

$$v = -\frac{1}{a}\frac{\Delta[A]}{\Delta t} = -\frac{1}{b}\frac{\Delta[B]}{\Delta t} = \frac{1}{c}\frac{\Delta[C]}{\Delta t} = \frac{1}{d}\frac{\Delta[D]}{\Delta t}$$

Thus, the correct answer is (b) and (e).

A common misconception is selecting Δ[NO]/Δt (alternative a), which does not account for the stoichiometric coefficient. Similarly,

choosing $\Delta[Cl_2]/\Delta t$ (alternative c) overlooks the fact that reactant consumption rates are negative, while product formation rates are positive.

Slide 2:

2. When a catalyst is added to the equilibrium, the rate of the forward reaction may?

$$2NO\ (g) + Cl_2\ (g) \rightleftharpoons 2NOCl\ (g)$$

   a. Increase
   b. Decrease
   c. None of above

Notes: A catalyst functions by lowering the activation energy of a reaction, increasing the rates of both the forward and reverse reactions without altering the equilibrium position. It helps the system reach equilibrium faster but does not shift it in either direction. Thus, the correct answer is (A) Increases. A common misconception is believing that a catalyst shifts the equilibrium toward the products or reactants.

However, the equilibrium position is determined by thermodynamic factors, such as temperature and concentration changes, rather than catalysts. Increasing the temperature accelerates both the forward and reverse reaction rates. Unlike catalysts, which only affect reaction speed, temperature changes also shift the equilibrium position based on the reaction's enthalpy change.

Slide 3:

3. What is the effect of adding helium gas (at constant volume) to an equilibrium mixture of the reaction:

$$CO\ (g) + Cl_2\ (g) \rightleftharpoons COCl_2\ (g) + heat$$

   a. The reaction shifts towards the products
   b. The reaction shifts towards the reactants
   c. Adding helium gas does not affect the equilibrium
   d. The reaction slows down

Notes: adding an inert gas like helium at constant volume does not change the partial pressures or concentrations of the reactants or products because the total volume remains the same. Since equilibrium position is dictated by changes in reactant or product concentrations (per Le Châtelier's principle), the equilibrium composition remains unchanged. Thus, the correct answer is (C) Adding helium gas does not affect the equilibrium. A common misconception is assuming that adding any gas will shift the equilibrium. However, only gases that participate in the reaction affect equilibrium when added or removed. However, if an inert gas is added under constant pressure instead of constant volume, equilibrium may be affected.
Slide 4: Factors Affecting Chemical Equilibrium: 1. Addition or removal of a reactant or product 2. A change in volume of the system, resulting in a change in concentration or partial pressure of the reactants and products 3. A change in temperature • Collision Theory: Change in the number of collisions Note: Several factors influence the equilibrium position of a reaction. First factor is the addition or removal of a reactant or product. Adding reactants shifts the equilibrium toward the products, while adding products shifts it toward the reactants. Conversely, removing a reactant or product has the opposite effect, causing the system to adjust in a way that replenishes the removed species. Another key factor is changes in volume or pressure, which particularly affect gaseous reactions. Decreasing the volume of a system increases the partial pressures of gases, favoring the side of the reaction with fewer gas molecules to counteract the pressure increase. In contrast, increasing the volume lowers pressure, favoring the side with more gas molecules as the system seeks to restore equilibrium. Temperature changes also play a crucial role in shifting equilibrium. For exothermic reactions, increasing temperature shifts equilibrium toward the reactants. Conversely, for endothermic reactions, increasing temperature shifts equilibrium toward the products, since the forward reaction absorbs heat. Lowering temperature has the opposite effect in both cases. From the perspective of collision theory, reaction rates depend on the frequency and energy of molecular collisions. Increasing temperature leads to more frequent and energetic collisions, which in turn accelerates both the forward and reverse reactions. However, while both reaction rates increase, the

equilibrium shift depends on whether the reaction is exothermic or endothermic.

3.3 Data Collection

In this study, both quantitative and qualitative data were collected. The quantitative data was obtained from the diagnostic test, while the qualitative data came from class observations and follow-up interviews. Data collection occurred over two consecutive semesters: Spring 2023 and Fall 2023. Each round followed the sequence shown in ***Figure 3-4***. In the Spring 2023 semester, there was a one-week interval between each step. For example, class observations were conducted one week after the distribution of the pre-assessment diagnostic test. The Fall 2023 semester had a two-week interval between each step in the sequence. These intervals were not determined by any specific research requirement but were based on my availability to conduct the study.

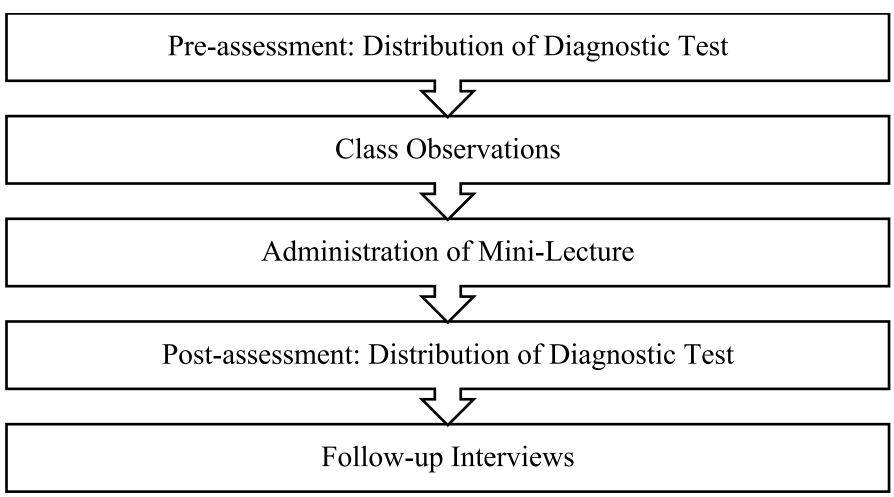

Figure 3-4 Sequence of Data Collection in Spring 2023 and Fall 2023

3.3.1 Distribution of Diagnostic Test (Pre and Post)

In Spring 2023, after obtaining IRB approval (see **Appendix B**), I met with each first-year CHEM 1 GTA individually during their spare time to conduct the pre-assessment. I explained the purpose of the research and emphasized that participation was entirely voluntary. I specifically reassured them that their performance on the diagnostic test was solely for research purposes and that no one, including their department supervisor, would have access to their performance data. Additionally, I clarified that their participation or test performance would not affect their GTA evaluations in any way.

If they chose to participate, they were required to sign a consent form. The form explicitly stated that by agreeing to participate, they would be expected to complete the full data collection sequence. Since the study was classified as exempt by the IRB, participants were asked to create a unique identifier by providing the first two letters of their favorite color and their shoe size in the consent form. This special code ensured that no personally identifiable information was collected during the study. The pre-assessment CEDT was distributed as a paper-and-pencil test.

After the mini-lecture (described in Section 3.3.3), I conducted the post-assessment by reaching out to the GTAs in person again to distribute the paper-and-pencil diagnostic test.

In Fall 2023, I coordinated with the professor who taught a required course for all first-year GTAs and received permission to administer both the pre-and post-assessments at the end of class. GTAs who chose to participate remained in the classroom to complete the consent form and the paper-and-pencil diagnostic tests.

3.3.2 Laboratory Class Observations

The class observations took place during the "Reversible Reactions" laboratory session. Prior to the experiment, I sent an email to first-year GTAs who had given consent for observations during the pre-assessment step. I asked them to forward the email to their students to notify them of my role as a researcher and inform them that I would be present in the lab for the first 10–15 minutes. In the email, I clarified that my primary focus was on observing the GTA's teaching, particularly how they explained chemical equilibrium concepts. However, I also noted that I might document the questions students asked during the session. Importantly, I assured students that no identifiable information would be recorded in my notes. If any student felt uncomfortable being observed, they were welcome to sit at the back of the room near the door.

Before each observation, I collected the TAs' special code again to ensure that the observation data could be properly matched with their pre- and post-assessment results. I utilized an open-ended note-taking approach with the aid of an observation protocol. The protocol (see **Appendix C**) consisted of two parts: one for descriptive notes documenting the GTA's teaching process and student interactions, and another for reflective notes, where I recorded my interpretations and insights. Generally, I spent around 15 minutes in each lab and left the room after notifying the GTA in both Spring 2023 and Fall 2023 semesters.

3.3.3 Implementation of Mini-Lecture to First-Year GTAs

In both the Spring 2023 and Fall 2023 semesters, after completing the "Reversible Reactions" laboratory session, I contacted the head TA to request permission to deliver a mini-lecture during the weekly TA meeting, which was held via Zoom. Upon receiving approval, I proceeded with the implementation.

Before each weekly TA meeting, the head TA typically sent out a reminder email to all CHEM 1 GTAs. I asked the head TA to include a notification in that email informing GTAs that I would be presenting a mini-lecture during the meeting and that participation was completely voluntary.

During the TA meeting, I waited until the head TA completed their presentation before delivering my mini-lecture. This arrangement ensured that GTAs who did not wish to participate could exit the Zoom meeting without missing any important TA meeting information. Once the head TA finished, I shared my screen and began my presentation.

I started by explaining the purpose of the mini-lecture to the GTAs and reminded them that they were free to leave if they did not wish to participate. Then, I conducted an interactive presentation using three multiple-choice questions designed to address common misconceptions. To encourage engagement, I used Zoom's polling feature, which allowed GTAs to respond anonymously. However, I also emphasized that participation in the poll was optional. When displaying the first question, I asked GTAs who chose to participate to submit a response by selecting any option. This allowed me to match their participation in the mini-lecture with their pre- and post-assessment presence for later data analysis. After giving the GTAs approximately three minutes to consider each question, I immediately explained the correct answer by reading through the notes I had prepared for each slide. Once I completed my presentation, I ended the Zoom meeting.

3.3.4 Follow-up Interviews

To gain GTAs' perceptions of the diagnostic test and the mini-lecture, I conducted semi-structured interviews. Semi-structured interviews are widely used in qualitative research because they provide flexibility while maintaining a structured approach to data collection. They allow researchers to explore participants' experiences, beliefs, and attitudes in greater depth by using open-ended yet guided questions.[113]

The interview protocol was designed to include leading questions that encouraged participants to reflect on their teaching experience and challenges. ***Table 3-5*** shows sample interview questions:

Table 3-5 Sample Interview Questions

1. How do you feel about the mini-lecture?
2. Do you think the mini-lecture is necessary for teaching assistants? Could you explain?
3. Can you describe what misconceptions you feel are most common in chemical equilibrium?
4. Do you think participating in the mini-lecture helped address your misconceptions? Please explain.
5. Did you feel you benefited from the mini-lecture? Why? Could you provide examples?
6. What could the department do to help you address your challenges in teaching, especially regarding chemistry content knowledge? Why? Could you provide examples?
7. If we were to launch this mini-lecture for every chapter, do you have any suggestions? How do you feel about this idea?

To recruit participants, I sent invitation emails to GTAs who had completed both the pre- and post-assessments and had attended the mini-lecture in both Spring 2023 and Fall 2023. Although participants had already provided consent for voice recording in the pre-assessment consent form, I sought their verbal confirmation again before starting each interview.

Interviews were conducted either in a private meeting room or via Zoom, depending on the participants' availability and preference. However, during data analysis, one participant from Fall 2023 chose to withdraw from the study. Therefore, I conducted an additional interview with another qualified GTA in Fall 2024. To ensure confidentiality, all participants will be assigned pseudonyms in the presentation of the results.

The timeline in ***Table 3-6*** provides an overview of the entire study. The initial IRB approval was obtained for instrument development, while the second IRB approval was for the official data collection.

Table 3-6 Timeline of the Entire Study

Process	Time Period
Initial IRB Approval	Fall 2022
Finalization of Research Questions, Diagnostic Instruments, and Mini-Lecture Development	Fall 2022
Second IRB Approval	Spring 2023
First-round Data Collection	Spring 2023
Second-round Data Collection	Fall 2023 (Fall 2024*)
Data Analysis	Fall 2024 – Spring 2025

3.4 Data Analysis

Data analysis was conducted in two main phases: quantitative analysis of the Chemical Equilibrium Diagnostic Test (CEDT) results and qualitative analysis of class observation notes and interview transcripts.

The quantitative data were obtained from the pre- and post-assessments using the Chemical Equilibrium Diagnostic Test (CEDT). These data were analyzed to identify misconceptions held by GTAs and to examine changes in their conceptual understanding of chemical equilibrium. Descriptive statistics were calculated, including mean scores, standard deviations, and percentages of correct responses. To evaluate the effectiveness of the mini-lecture intervention, a mixed ANOVA was conducted using SPSS (version 29.0). Statistical significance was determined at an alpha level of 0.05.

Qualitative data included classroom observation notes and semi-structured interview transcripts. After each lab observation, I transcribed the open-ended notes into narrative descriptions to capture the flow and content of the GTAs' instruction. These narratives were analyzed to identify any misconceptions conveyed by GTAs to students and to provide contextual insights that support the interpretation of the quantitative findings.

Interview recordings were transcribed verbatim. A thematic analysis approach was used to analyze the transcripts. I reviewed the transcripts multiple times to gain familiarity with the data. Open coding was then conducted to identify recurring concepts and patterns. These initial codes were subsequently grouped into broader thematic categories, allowing for the identification of key themes related to GTAs' perceptions of the mini-lecture's usefulness and effectiveness.

In the final phase, quantitative and qualitative data were integrated. The quantitative results uncovered patterns in conceptual understanding before and after the intervention, while the qualitative findings offered depth and explanation for these patterns. This mixed-methods integration provided a comprehensive understanding of both the misconceptions GTAs held and their perceptions to the mini-lecture intervention.

3.4.1 Validity and Reliability

Validity refers to the extent to which a study measures what it intends to measure.[114] To enhance the validity of the study, I used the strategy "triangulation" by collecting data from multiple sources, including pre- and post-assessments, classroom observations, and semi-structured interviews. Each source provided a different lens through which to understand the GTAs' conceptual understanding and teaching practices.

For example, a misconception identified in a GTA's CEDT response, such as misapplying Le Châtelier's principle, was cross-checked against classroom observation notes to determine whether that same misconception was conveyed during instruction. In this way, I could verify that such misconceptions were not due to chance but reflected actual conceptual difficulties.

Reliability refers to the consistency and replicability of the findings.[114] To strengthen the reliability of this study, I implemented intercoder reliability method during the thematic analysis of interview transcripts. A second rater with a background in chemical education independently coded the transcripts using the same coding scheme. We then compared coding results and discussed any discrepancies. The reliability coefficient was calculated to be 0.87, which indicates a high level of agreement and supports the consistency of the coding process.

3.5 Reflexivity of the Role of the Researcher

As an educational researcher, I am inherently part of the research process, and my prior experiences, assumptions, and beliefs inevitably influence the way I conduct research. Researcher reflexivity is essential for ensuring the trustworthiness of data and findings. Reflexivity can be examined through introspective, methodological, and epistemological standpoints.[115] To operationalize reflexivity, researchers may consider the following three questions.[116, 117]:

1. How has my personal history influenced the choice of topic?
2. What personal values may shape the research process?
3. What advantages and barriers might my personal background and professional competence introduce during data collection and analysis?

My academic background has played a significant role in shaping this study. I earned my bachelor's degree in pure chemistry from a university dedicated to preparing future K–12 educators. This learning environment nurtured my interest in educational studies, ultimately leading me to pursue a Ph.D. in chemical education. In addition to conducting research, I have worked as a chemistry teaching assistant and a CHEM 1 lecture instructor for several years during my Ph.D. journey. Teaching the same content each semester allowed me to observe that chemical equilibrium remains one of the most challenging concepts for students to grasp. At the same time, I underwent my own process of identifying and correcting misconceptions about chemical equilibrium. These experiences strongly influenced my decision to focus on this topic.

In this study, my role can be defined as both an instrument and an observer. As a chemical education researcher, I have been trained in various research methodologies, and my coursework in qualitative and quantitative methods has equipped me with the necessary skills to design research instruments, select appropriate data analysis techniques, and effectively report findings. These skills and experiences contribute to the validity and reliability of my study.

While my background in chemical education and experience as a TA have informed the study's framework, they also introduce potential biases. I hold the belief that TAs play a crucial role in shaping students' understanding, both formally and informally. Additionally, I believe that misconceptions can be effectively addressed through proper instructional practices. Recognizing these biases is crucial to maintaining objectivity. Bracketing my preconceptions throughout the research process is essential to ensuring that my findings remain as unbiased and rigorous as possible.

Chapter 4 Results and Discussions

The Results and Discussions section is organized according to the sequence of the research questions guiding this study. The analysis begins with the GTAs' pre-assessment performance on the Chemical Equilibrium Diagnostic Test (CEDT), which identifies their initial misconceptions about chemical equilibrium. Then, the focus shifts to how these misconceptions are reflected in the GTAs' instructional practices during the "Reversible Reactions" laboratory session, serving as a form of validation. Next, the results examine whether GTAs exhibit fewer misconceptions after participating in the mini-lecture designed to address these common conceptual difficulties. Finally, the section concludes with an exploration of GTAs' perceptions of the mini-lecture and their suggestions for additional support. This qualitative feedback provides insight into their preferences for future instructional training.

4.1 GTAs' Misconceptions Identified from the Pre-Assessment in Spring 2023 and Fall 2023

The final version of the Chemical Equilibrium Diagnostic Test (CEDT) is divided into two sections. The first section consists of three questions designed to assess participants' prerequisite knowledge of chemical equilibrium, specifically their understanding of reaction rates. The second section consists of one comprehensive question on chemical equilibrium with five sub-questions. Each sub-question contains multiple-choice items ranging from one item to four items, making a total of 11 multiple-choice questions in this section.

The correct response for each item is worth one point each, with the maximum score for the first section being 3 points, the maximum score for the second section 11 points, making the total possible score for the CEDT 14 points.

GTAs' overall performance on the pre-assessment is summarized in ***Table 4-1***. The average score for first-year GTAs in Spring 2023 was 7.10 (N=10), while in Fall 2023, it was 5.82 (N=13). The independent samples t-test found no significant difference in the mean scores between the two cohorts, $t(19) = -1.836$, $p = 0.082$. These results indicate that, despite being admitted to a doctoral program, GTAs still exhibited misconceptions regarding chemical equilibrium. To identify the specific misconceptions held by the participants, a detailed analysis of individual test items was conducted.

Table 4-1 Average Pre-Assessment Scores of GTAs on the CEDT in Spring and Fall 2023

	Spring 2023 (N=10)		Fall 2023 (N=11)	
	Mean	SD	Mean	SD
Performance Scores	7.10	1.29	5.82	1.83

As noted earlier, the CEDT consists of two sections. The following analysis first presents GTAs' performance on each section separately, followed by a discussion of the specific misconceptions identified in their responses.

4.1.1 GTAs' Misconceptions Identified from First Section in the Pre-Assessment

- *Question 1: Consider a reaction where chemicals 'A' and 'B' react to form 'C', A+B→C. Explain in your own words what you understand by the term "rate of reaction."*

Since this was an open-ended question, a scoring rubric was developed using a flexible, concept-based approach by reviewing textbook definitions and GTAs' responses (see ***Table 4-2***).[118] Each criterion was assigned one point if the corresponding key concept appeared in the GTA's explanation. In general, responses were considered acceptable if they included keywords such as "concentration change over time," "how fast," "rapidity," or "speed," even if the phrasing was somewhat vague or general.

Table 4-2 Dichotomous Grading Criteria for GTAs' Responses to Question 1 on the CEDT

Criteria	**Description**
Increased Kinetic Energy	*The response states that an increase in temperature raises the kinetic energy of the reacting molecules. This is key to understanding why the reaction rate increases.*
Effective Collisions	*The answer explains that the increased kinetic energy leads to more frequent and/or more effective collisions between reactants, resulting in a higher reaction rate.*
Arrhenius Equation	*The response includes the Arrhenius equation,* $k = Ae^{-\frac{E_a}{RT}}$ *or refers to its implications, such as the exponential relationship between temperature and reaction rate (i.e., more molecules overcoming the activation barrier).*

To evaluate the precision of the scoring rubric and ensure interrater reliability, Cohen's Kappa was calculated. I first graded the GTAs' responses using the rubric, and a second rater, a doctoral student in chemistry, independently graded the same responses using the same rubric. The resulting value of κ = 0.89 indicates a high level of agreement between the two raters, suggesting that the rubric was both clear and reliably applied.

Table 4-3 GTAs' Responses to Question 1 on the Pre-Assessment (Spring 2023)

	TAs' responses	Score
TA1	*"Rate of reaction means the speed of reactants consumption or product generation."*	1
TA2	*"The rate at which A and B reacts to form product C."*	1
TA3	*"The rate of the reaction is determined by the concentration of reactants."*	0
TA4	*"How fast the reaction occurs."*	1
TA5	*"How the reaction changes in respect to products and reactants, how fast a reaction proceeds."*	1
TA6	*"How fast or slow a rxn proceeds (speed)."*	1
TA7	*"The rate of the reaction signifies how quickly reactants A & B convert to chemical "C". So it signifies the amount in moles/L reacted in a specific period of time."*	1
TA8	*"Rate of Rxn is a term used to explain the speed of reaction."*	1
TA9	*"Rates of reaction is how fast the reaction is happening."*	1
TA10	*"Rate of reaction can be defined as the speed of reaction that take place. Based on the concentration of reactants, it can determine if the reaction will be forward or reverse."*	0
	Correct Answers%	8/10 (80%)

Table 4-3 presents GTAs' responses to Question 1 from the Spring 2023 pre-assessment. Based on the scoring rubric, 8 out of 10 responses were graded as correct, while 2 were marked as incorrect. These results suggest that the majority of GTAs were able to articulate a basic understanding of the concept of reaction rate. However, it is important to note that only one respondent (TA7) provided a definition closely aligned with the IUPAC definition, explicitly referring to the

change in concentration of reactants or products over time. The remaining correct responses tended to define reaction rate in more general terms, using language such as “speed” or “rapidity,” without mentioning concentration over time.

Two responses, from TA3 and TA10, were graded as incorrect. TA3 stated that “*the rate of the reaction is determined by the concentration of reactants.*” This response identifies a factor that affects the reaction rate, rather than defining the rate itself. Although it does not directly address the meaning of reaction rate, it demonstrates some awareness of the rate law. Therefore, I do not consider this response to reflect a misconception.

On the other hand, TA10’s response reflects a misconception. The first sentence defines rate as the speed of the reaction, which is generally acceptable. However, the second sentence claims that the rate determines whether the reaction proceeds forward or in reverse. This indicates a misunderstanding of the difference between reaction rate and reaction direction.

Reaction rate refers to how fast a reaction occurs, while the direction in which a reaction proceeds is determined by thermodynamic factors such as the equilibrium constant. At equilibrium, the forward and reverse reactions occur at equal rates, but this does not mean that the rate determines direction; it simply reflects a dynamic balance. TA10’s response was therefore scored as incorrect and interpreted as demonstrating a conceptual misunderstanding.

Table 4-4 TAs’ Responses to Question 1 on the Pre-Assessment (Fall 2023)

	TAs’ responses	Score
TA1*	*“Rate of reaction in the amount of product formed over a period of time by the reactants.”*	1

TA2*	*"The amount of product C produced in a unit time of reaction."*	1
TA3*	*"Reaction rate is the time it takes for A and B to be consume to produce C."*	0
TA4*	*"Rate of appearance of C or rate of disappearance of A & B with respect to time is called rate of reaction."*	1
TA5*	*"The "speed" at which A and B are converted to C. This is influenced by many factors, such as temperature, pressure, catalysis, etc."*	1
TA6*	*"This how rapid reactants or substrates are being converted to product."*	1
TA7*	*"The rate of reaction can be consider as a measurement of how fast the chemical reactions take place."*	1
TA8*	*"The rate of the reaction is the concentration of products over the concentration of reactants."*	0
TA9*	*"Rate of reaction is also called speed of reaction, it means how much time it will take to form product."*	0
TA10*	*"Rate of reaction means per second or minute how much reactant (A+B) converted into product (C)"*	1
TA11*	*"The rate of the reaction is how quickly the reaction turns A+B into C."*	1
	Correct Answers%	8/11 (73%)

Table 4-4 presents GTAs' responses to Question 1 from the Fall 2023 pre-assessment. Based on the established scoring rubric, 8 out of 11 responses were marked as correct, resulting in a correct response rate of 73%. This indicates that the majority of GTAs in Fall 2023 were able to articulate a basic understanding of reaction rate.

Among the correct responses, four GTAs (TA1*, TA2*, TA4*, and TA10*) provided definitions that closely aligned with the IUPAC definition, referring to the amount of product formed or reactant consumed over a specific period of time. The other four correct responses (TA5*, TA6*, TA7*, and TA11*) only used general language, such as "speed" or "how quickly."

Three responses (TA3*, TA8*, and TA9*) were graded as incorrect. TA3* and TA9* both defined the rate of reaction as the time it takes to form the product. It reflects a misconception by confusing reaction rate with time to completion. In contrast, TA8* stated that the rate of reaction is the concentration of products over the concentration of reactants. This definition is incorrect and indicates a deeper misconception, in which reaction rate is confused with the equilibrium constant.

- *Question 2: The* $Mg\ (s) + 2HCl\ (aq) \rightarrow MgCl_2\ (aq) + H_2\ (g)$ *reaction experiment was carried out. An increase in temperature can cause an increase in the reaction rate. The proper explanation for this is…*

Since this was an open-ended question, a scoring rubric was developed to evaluate GTAs' responses. Responses that mentioned "kinetic energy," "collision theory," or the Arrhenius equation to explain why an increase in temperature leads to a higher reaction rate were considered correct. ***Table 4-5*** presents the dichotomous scoring rubric. GTAs received one point if their response matched any one of the listed criteria.

Table 4-5 Dichotomous Grading Criteria for GTAs' Responses to Question 2 on the CEDT

Criteria	**Description**
Increased Kinetic Energy	*The response states that an increase in temperature raises the kinetic energy of the reacting molecules. This is key to understanding why the reaction rate increases.*
Effective Collisions	*The answer explains that the increased kinetic energy leads to more frequent and/or more effective collisions between reactants, resulting in a higher reaction rate.*

Arrhenius Equation	*The response includes the Arrhenius equation,* $k = Ae^{-\frac{E_a}{RT}}$ *or refers to its implications, such as the exponential relationship between temperature and reaction rate (i.e., more molecules overcoming the activation barrier).*

To evaluate the precision of the rubric and consistency between raters, interrater reliability was calculated using Cohen's Kappa. The resulting value of κ = 1 indicates an almost perfect agreement between raters. This suggests that the scoring rubric was sufficiently clear and that the raters applied it with a high level of consistency.

Table 4-6 GTAs' Responses to Question 2 on the Pre-Assessment (Spring 2023)

	TAs' responses	Score
TA1	*"The high temperature provides higher kinetic energy, leading the more frequent collision of Mg and HCl which increases the rate."*	1
TA2	*"It suggests that the reaction is endothermic."*	0
TA3	*"Higher temperatures can increase energy in molecules allowing them to move around faster and react quicker."*	1
TA4	*"You are adding energy into the system which allows bond breaking."*	1
TA5	*"Increase temp. cause an increase in molecular movement.* $\Delta G = \Delta H - T\Delta S$.*"*	0
TA6	*"Heat acted as a catalyst: ↑T = ↑Rate."*	0
TA7	*"Increase in temperature may increase the kinetic energy of the species involved and may lead to increased rate of the reaction. The K.E. increase if the reason."*	1
TA8	*"On increasing the temperature, reaction rate increases because temperature provides thermal energy that helps the reactants to cross the energy barriers at a faster rate to form products."*	1
TA9	*"Heat can be a catalyst because it excites molecules."*	0
TA10	*"The reaction is endothermic. That's why increasing temperature will favor the product."*	0
	Correct Answers%	5/10 (50%)

Table 4-6 summarizes GTAs' performance on Question 2 from the Spring 2023 pre-assessment. Only 50% of the participants answered the question correctly.

Five GTAs demonstrated appropriate conceptual understanding. TA1 explicitly mentioned molecular collisions, while TA3 and TA7 connected increased temperature to higher kinetic energy, which in turn increases the rate of reaction. TA4 and TA8 correctly linked higher temperature to the energy needed for bond breaking or overcoming activation energy barriers, which also results in an increased reaction rate. These responses were considered acceptable.

However, the remaining five GTAs exhibited notable misconceptions. TA2 and TA10 stated that an increase in temperature increases the rate of reaction because the reaction is endothermic. This reflects a significant misconception, as they appear to be applying equilibrium concepts rather than kinetic reasoning. While temperature can shift the position of equilibrium in an endothermic reaction, this is not the correct explanation for an increase in reaction rate.

TA5 initially stated that higher temperature increases molecular motion, which is acceptable. However, the inclusion of the Gibbs free energy equation indicates confusion between thermodynamic spontaneity and reaction kinetics. This suggests that TA5 was attempting to explain the effect of temperature in terms of spontaneity rather than reaction rate.

Finally, TA6 and TA9 both described heat or increased temperature as acting like a catalyst, which is a misconception. While both a catalyst and increased temperature can speed up a reaction, they do so via different mechanisms. A catalyst works by lowering the activation energy, providing an alternative reaction pathway, whereas increasing temperature allows more reactant particles to surpass the existing activation barrier due to increased kinetic energy.

Table 4-7 GTAs' Responses to Question 2 on the Pre-Assessment (Fall 2023)

	TAs' responses	Score
TA1*	*"The increase in temperature is facilitating in the reaction to shift the equilibrium towards the forward direction."*	0
TA2*	*"The reaction is endothermic in the forward direction."*	0
TA3*	*"Rate of reaction can be affected by concentration."*	0
TA4*	*"The reaction is endothermic, and it needs heat. Thus, supplying heat will increase the rate of reaction."*	0
TA5*	*"This will increase the number and strength of molecular collisions in the aqueous solution, causing more reactions."*	1
TA6*	*"An increase in temperature causes an increase in collision of the molecules of the reactant and this in turn drives how the substrate reacts."*	1
TA7*	*"It will increase the kinetic energy of molecules."*	1
TA8*	*"As temp increases, the average speed of reactants increases. This causes more collisions to happen and thus greater rate of reaction."*	1
TA9*	*"Generally, depends on the nature of reaction. The rxn is exothermic or endothermic. In the above reaction, increasing temp can increase the rate of reaction because kinetic energy increases."*	0
TA10*	*"This reaction could be described as being endothermic, that is heat can be treated as a reagent."*	0
TA11*	*"Increasing temperature makes the molecules of the reactant get more energy to bind together which increases the rate of reaction. Increase in temperature always increase entropy and as such increase reaction rate."*	0
	Correct Answers%	4/11 (36%)

Table 4-7 summarizes GTAs' performance on Question 2 from the Fall 2023 pre-assessment. Only 4 out of 11 participants (36%) answered the question

correctly. Among these, TA5*, TA6, and TA8* explicitly referred to collision theory, while TA7* correctly explained that increasing temperature raises the kinetic energy of particles, which leads to a higher reaction rate.

The remaining seven responses revealed a range of misconceptions. TA1* incorrectly attributed the increase in reaction rate to an equilibrium shift. It reflects a misconception of the difference between kinetics and thermodynamics. Similarly, TA2*, TA4*, and TA10* claimed that temperature increases the rate because the forward reaction is endothermic, once again wrongly applying equilibrium-based reasoning rather than kinetic principles.

Although TA9* correctly noted that increasing temperature increased kinetic energy, the response also stated that the effect of temperature on reaction rate depends on whether the reaction is exothermic or endothermic. This reflects the same misconception seen in TA2*, TA4*, and TA10*, where thermodynamic reasoning was incorrectly applied to a kinetic concept.

TA3* stated that reaction rate can be affected by concentration, which is a true statement in general but does not address the effect of temperature, as required by the question.

Finally, TA11*'s response reflected a misconception by stating that an increase in temperature leads to an increase in entropy, which in turn increases the reaction rate. Entropy is a thermodynamic property related to the disorder of a system, but it does not directly influence the reaction rate. TA11*'s explanation therefore indicates an incorrect application of a thermodynamic idea in a kinetic context.

- *Question 3: At a temperature of 25 °C a reaction occurs as follows:*

$$Na_2S_2O_3\ (aq) + 2HCl\ (g) \rightarrow 2NaCl\ (aq) + \ H_2O\ (l) + SO_2\ (g) + S\ (s)$$

If the rate of formation of sulfur is 2 mol/min, then…

(A) the rate of reduction of sodium thiosulfate is 1 mol/min

(B) the rate of formation of sodium chloride is 4 mol/min

(C) the rate of formation of sulfur dioxide is 1 mol/min

(D) the rate of formation of sodium chloride is 2 mol/min

Based on the information above, can you determine the rate of the reaction? If yes, explain how/If no, explain why

Question 3 consists of a multiple-choice item followed by an open-ended justification. The correct answer is (B). GTAs who selected option B, regardless of whether they provided a correct explanation in the open-ended portion, were awarded one point.

Table 4-8 GTAs' Responses to Question 3 on the Pre-Assessment (Spring 2023)

	TAs' Choices	TAs' responses	Score
TA1	*B*	*"Yes, because of stoichiometry."*	1
TA2	*B*	"IDK."	1
TA3	*B*	*"No, you need another scenario with varying concentration."*	1
TA4	*B*	*"Yes, Products are formed at a rate of 1 mole/30 seconds."*	1
TA5	*D*	*"Yes, use equation and find equilibrium constant K,* $rate = K\,\frac{[Products]^x}{[Reactants]^y}$*."*	0
TA6	*B*	-	1
TA7	*B*	*"Yes, the rate of formation of all reactants can be determined by taking care of the stoichiometry."*	1
TA8	-	*"No, the rate of HCl is not given and rate depends on reactants' concentration."*	0

TA9	*B*	*"No, the rate of one element doesn't determine rate of entire reaction."*	1
TA10	-	*"No. rate is equal to change of reactant or product over time. Time is not provided."*	0
		Correct Answers%	7/10(70%)

Table 4-8 presents GTAs' responses to Question 3 from the Spring 2023 pre-assessment. Overall, 70% of participants selected the correct answer (Option B), indicating a general understanding of how stoichiometric relationships can be used to interpret the rates of specific reactants or products.

Based on their open-ended responses regarding how to determine the rate of the overall reaction, TA1, TA4, and TA7 explicitly referenced stoichiometry in their justifications. These responses reflect an appropriate conceptual grasp of how reaction rates of different substances relate based on their stoichiometric coefficients.

On the other hand, the remaining responses revealed some confusion and misconceptions. TA3, TA8, and TA9 argued that the rate of the reaction could not be determined without knowing the concentrations of the reactants. This suggests that these participants were attempting to apply rate law reasoning, in which the reaction rate depends on concentration and reaction order. While not necessarily a misconception, these responses reflect a misalignment between the context of the question and the concept they were trying to apply.

In contrast, TA5 wrote an equation $rate = K\,\frac{[Products]^x}{[Reactants]^y}$ and stated that the rate of reaction could be determined by finding the equilibrium constant K. This indicates a misconception between the rate law and the equilibrium constant expression, suggesting a confusion between reaction kinetics and thermodynamic equilibrium.

Table 4-9 GTAs' Responses to Question 3 on the Pre-Assessment (Fall 2023)

	TAs' Choices	*TAs' responses*	Score
TA1*	-	*"Yes."*	0
TA2*	*B*	*"No, because we don't know the value of rate constant."*	1
TA3*	*B*	*"Yes,* $Rate = [Product]/[Reactant] \cdot Time$*."*	1
TA4*	*A*	-	0
TA5*	*ABC*	*"Yes, given this information you can determine rate.* $K_c = \frac{d[Products]}{d[Reactants]}$*."*	0
TA6*	-	*"No, information B and D above appears to be contrasting."*	0
TA7*	-	-	0
TA8*	*B*	*"Yes, it's given at 2 mol/min."*	1
TA9*	*B*	*"Yes, to determine the rate of reaction we need molar concentration of reactants and products."*	1
TA10*	*A*	*"rate of reduction of reactant and rate of formation of product should be same."*	0
TA11*	*B*	*"No, I think we need more formation rates at differing temperatures."*	1
		Correct Answers%	5/11(45%)

Table 4-9 presents GTAs' responses to Question 3 from the Fall 2023 pre-assessment. Only 5 out of 11 participants (45%) selected the correct answer (Option B).

When answering whether they could determine the rate of the overall reaction, among those who selected the correct option, only TA8* and TA9* demonstrated an acceptable conceptual understanding. Although TA2* and TA11* chose the correct answer, their explanations appeared to reference the rate law. TA3* selected the correct alternative but provided an incorrect equation,

"$Rate = [Product]/[Reactant] \cdot Time$". It reflects a misconception regarding both the rate law and the equilibrium constant expression.

The remaining six GTAs selected incorrect alternatives, and their open-ended responses revealed a variety of misconceptions. TA1*, TA4*, and TA7* showed a lack of understanding of how to use stoichiometric relationships to interpret reaction rates, as they either did not answer the question or chose the wrong alternative without providing any explanation.

TA6* appeared to misinterpret the purpose of the multiple-choice alternatives, treating them as provided data for calculating the rate of reaction. TA10* correctly stated that the rate of reduction of a reactant and the rate of formation of a product should be the same, but incorrectly selected Option A. These responses indicate a lack of understanding of how to apply stoichiometric relationships to determine relative reaction rates.

Lastly, TA5* wrote an equation, $K_c = \frac{d[Products]}{d[Reactants]}$, which appears to be based on the equilibrium constant expression but does not represent either a valid rate law or equilibrium expression. It reflects a misconception about the difference between the concepts of reaction rate and chemical equilibrium.

The purpose of this question was to assess whether GTAs could accurately recall the mathematical definition of reaction rate, particularly the difference between moles and concentration. According to the IUPAC definition, the rate of a chemical reaction is expressed as the change in concentration of a reactant or product per unit time. For a general reaction of the form:

$$aA + bB \rightleftharpoons cC + dD$$

the reaction rate can be written as:

$$v = -\frac{1}{a}\frac{\Delta[A]}{\Delta t} = -\frac{1}{b}\frac{\Delta[B]}{\Delta t} = \frac{1}{c}\frac{\Delta[C]}{\Delta t} = \frac{1}{d}\frac{\Delta[D]}{\Delta t}$$

Since the definition of reaction rate is based on concentration, it applies primarily to aqueous and gas-phase substances. Solids and pure liquids are excluded because their concentrations remain constant.

In this question, the rate of sulfur formation is provided in units of moles per minute (2 mol/min). However, without knowing the volume of the reaction system, we cannot convert this value into a true reaction rate expressed in terms of concentration over time (mol/L·min). Therefore, from a strict kinetic standpoint, the rate of reaction cannot be fully determined with the information given.

Interestingly, only one GTA (TA9*) from Fall 2023 clearly demonstrated awareness of this issue by stating, "to determine the rate of reaction we need molar concentration of reactants and products." Although other participants correctly used stoichiometry to estimate rates of other substances based on the sulfur formation rate, they implicitly treated moles per minute as equivalent to concentration per minute. This subtle but important misconception will be further examined in the second section of the assessment as well.

Summary of Findings from the First Section of the CEDT:

From GTAs' responses to the first section of the CEDT in both the Spring and Fall semesters, several recurring misconceptions were identified (***Table 4-10***).

These included ***confusion between reaction rate and reaction time***, the ***use of thermodynamic reasoning to explain kinetic phenomena***, and ***attempts to apply equilibrium constant expressions to calculate reaction rates***. In the following section of the CEDT, we aim to examine whether these misconceptions persisted following the intervention and whether GTAs carried them into more complex reasoning tasks.

Table 4-10 Summary of Misconceptions Identified in the First Section of the CEDT

Misconception	Spring 2023 (GTA#)	Fall 2023 (GTA#)
Question 1		
Confusing reaction rate with reaction direction (i.e., rate determines reaction direction)	TA10	-
Confusing reaction rate with reaction time/time to completion	-	TA3*, TA9*
Confusing reaction rate with the equilibrium constant	-	TA8*
Question 2		
Stating that temperature increases the rate because the reaction is endothermic	TA2, TA10	TA1*, TA2*, TA4*, TA9*, TA10*
Describing temperature as a catalyst	TA6, TA9	-
Explaining the increase in rate using Gibbs free energy or entropy	TA5	TA11*
Question 3		
Lack of understanding of how to apply stoichiometry to calculate rates	TA10	TA1*, TA4*, TA7*
Treating moles per minute as equivalent to concentration per minute	All GTAs	All except TA9*
Writing incorrect equations for both the rate law and equilibrium constant	TA5	TA3*, TA5*

4.1.2 GTAs' Misconceptions Identified from Second Section in the Pre-Assessment

The second section consists of one comprehensive question on chemical equilibrium with five sub-questions and a possible total score of 11. The questions asked GTAs to predict how changes in temperature, pressure, and concentration would affect the equilibrium system.

- *Consider an equilibrium mixture of CO, Cl_2, $COCl_2$ at 200 °C and 1 atmosphere pressure present in chemical equilibrium:*

$$CO\ (g) + Cl_2\ (g) \rightleftharpoons COCl_2\ (g) + heat$$

Responses for questions (1) to (5) are to be given as: A: greater than the initial amount; B: less than initial amount; C: same as the first equilibrium; D: data insufficient for conclusion

(1) The mixture is cooled to 150 °C, keeping the volume constant. When the system returns to a new equilibrium,

(a) the mass of $COCl_2$ present will be...

(b) the rate at which $COCl_2$ is being formed will be...

(c) the equilibrium constant will be…

(2) The volume of the system is halved by increasing pressure at constant temperature. When the system returns to a new equilibrium,

(a) the mass of $COCl_2$ present will be...

(b) the concentration of $COCl_2$ present will be...

(c) the mass of CO present will be...

(d) the concentration of CO present will be...

(3) Some Cl_2 is removed from the system, the volume and the temperature being kept constant. When the system returns to a new equilibrium,

(a) the mass of CO will be…

(b) the equilibrium constant will be...

(4) 1 mole $COCl_2$, and 0.01 mole Cl_2 is added to the system at constant volume and temperature. When the system returns to another equilibrium, how does the mass of CO change? Include the rational.

(5) When temperature is increased, the rate of the forward reaction will

(a) Increase

(b) Decrease

(c) Unchanged

(d) Data insufficient for conclusion

Table 4-11 GTAs' Responses to the Second Section of the CEDT (Spring 2023 Pre-Assessment)

Question	Correct Answer	A%	B%	C%	D%	No Response	Others	Correct Answers%
Equilibrium Shift								
Q1a	A	4	6	-	-	-	-	4/10 (40%)
Q2a	A	8	-	2	-	-	-	8/10 (80%)
Q2c	B	1	7	2	-	-	-	7/10 (80%)
Q3a	A	9	-	1	-	-	-	9/10 (90%)
Relating Reaction Rate and Equilibrium								
Q1b	B	3	6	1	-	-	-	6/10 (60%)
Q5	A	4	4	1	1	-	-	4/10 (40%)
Changes in Concentration at Equilibrium								
Q2b	A	7	-	3	-	-	-	7/10 (70%)
Q2d	A	1	7	2	-	-	-	1/10 (10%)

Equilibrium Constant Understanding								
Q1c	A	-	4	6	-	-	-	0/10 (0%)
Q3b	C	2	3	5	-	-	-	5/10 (50%)
Q4	D	7	1	1	-	1	-	0/10 (0%)

Analysis of GTAs' results was based on four conceptual areas: equilibrium shift, reaction rate, concentration changes at equilibrium, and equilibrium constant understanding. According to previous studies[119, 120], a response is considered to reflect a common misconception if it is selected by 20% or more of participants. I adopted this threshold to identify misconceptions by examining incorrect alternatives chosen by more than 20% of GTAs.

Table 4-11 presents the percentage of correct responses for each item from the Spring 2023 pre-assessment. Overall, GTAs demonstrated a relatively strong grasp of equilibrium shifts by applying Le Châtelier's Principle. However, their performance declined on items requiring more quantitative or conceptual reasoning, particularly in interpreting concentration changes and understanding how the equilibrium constant is affected.

In Question 1a, 60% of GTAs incorrectly believed that decreasing temperature would shift an exothermic equilibrium system backward, indicating a misconception of how temperature influences equilibrium position. In Question 1b, which asked how the rate of product formation changes with a decrease in temperature, 30% of GTAs stated that the rate would increase. Notably, these same GTAs answered Question 1a correctly, suggesting that although they understood the direction of equilibrium shift, they mistakenly assumed that a shift toward products also implies an increased reaction rate. This reveals a misconception in which GTAs overlook the effect of temperature on reaction kinetics and mistakenly apply equilibrium shift reasoning to predict changes in reaction rate.

Question 5 provided further evidence of confusion between kinetics and thermodynamics. 40% of GTAs believed that increasing the temperature of an exothermic reaction would decrease the forward reaction rate. This suggests that they incorrectly applied Le Châtelier's Principle, which describes changes in equilibrium position, to reasoning about reaction rate.

Misconceptions about concentration were especially evident in Question 2d. Only one GTA answered correctly, while 70% believed that the concentration of carbon monoxide would decrease when the volume of the system was halved. Although halving the volume would shift the equilibrium toward the product side, thereby reducing the amount (in moles) of CO, the concentration of CO actually increases due to the reduced volume. This indicates a misconception between amount and concentration, and possibly a failure to consider the effect of volume explicitly. It is likely that many GTAs assumed volume to be constant, as it often is in equilibrium problems in general chemistry. Over time, this assumption may have become so ingrained that they subconsciously ignored volume changes even when they were central to the question.

A widespread misconception of the equilibrium constant was also observed. In Question 1c, no GTA selected the correct answer. 40% believed that decreasing the temperature would decrease the equilibrium constant, while the remaining 60% believed that temperature had no effect on it. Similarly, in

Question 3b, 50% of GTAs believed that removing a reactant would cause the equilibrium constant to either increase or decrease, despite the fact that changes in concentration do not affect the value of K when the temperature remains constant.

The correct answer to Q4 is D (data insufficient for conclusion) because solving the question requires setting up a mathematical equation using the equilibrium constant expression. Without the numerical value of the equilibrium constant and the initial concentrations of all species at first equilibrium, it is not possible to determine the direction or extent of the shift, nor to calculate the resulting mass of CO. Any attempt to answer such questions without this information reflects a misunderstanding and an overreliance on Le Châtelier's Principle as a tool for quantitative reasoning.

Table 4-12 summarized the misconceptions identified in the second section of the CEDT from Spring 2023 pre-assessment.

Table 4-12 Summary of Misconceptions Identified in the Second Section of the CEDT (Spring 2023 Pre-Assessment)

Question(s)	Misconception	Percentages
Q1a	Belief that decreasing temperature shifts an exothermic reaction backward	60%
Q2a, 2c	Belief that halving the volume does not cause an equilibrium shift	20%
Q1b, Q5	Misapplication of Le Châtelier's Principle to predict changes in reaction rate	30%, 40%
Q2d	Confusion between mass and concentration	70%
Q1c	Belief that temperature has no effect or decreases the equilibrium constant	100%
Q3b	Belief that removing a reactant alters the value of the equilibrium constant	50%
Q4	Belief that changes in mass can be determined without the equilibrium constant or concentrations	100%

In the Fall 2023 semester, GTAs' responses exhibited greater variation compared to those from Spring 2023, as shown in ***Table 4-13***.

Table 4-13 GTAs' Responses to the Second Section of the CEDT (Fall 2023 Pre-Assessment)

Question	Correct Answer	A	B	C	D	No Response	Others	Correct Answers%
Equilibrium Shift								
Q1a	A	6	1	3	1	-	-	6/11 (55%)
Q2a	A	5	1	2	3	-	-	5/11 (45%)
Q2c	B	1	6	3	1	-	-	6/11 (55%)
Q3a	A	5	4	2	-	-	-	5/11 (45%)
Relating Reaction Rate and Equilibrium								
Q1b	B	6	2	-	3	-	-	2/11 (18%)
Q5	A	3	5	1	1	-	-	3/11 (27%)
Changes in Concentration at Equilibrium								
Q2b	A	10	1	-	-	-	-	10/11 (91%)
Q2d	A	4	6	-	1	-	-	4/11 (36%)
Equilibrium Constant Understanding								
Q1c	A	3	1	2	5	-	-	3/11 (27%)
Q3b	C	1	3	3	4	-	-	3/11 (27%)
Q4	D	4	1	1	-	4	1	0/11 (0%)

Overall, only about half of the participants correctly identified how equilibrium shifts in response to changes in temperature, pressure, and concentration. In Question 1a, 3 out of 11 GTAs (27%) believed that decreasing the temperature would not cause any shift in the equilibrium, indicating a misconception about how temperature affects equilibrium position. In Question 2a, three GTAs selected "data insufficient" when asked how equilibrium would shift if the volume were halved at constant temperature. In Question 3a, four GTAs (36%) believed that removing one reactant would cause the amount of the other reactant to decrease. These responses suggest that some GTAs viewed the reactants as passively linked, assuming that removing one automatically reduces the other.

Regarding reaction rate, in Question 1b, more than half of the GTAs (6 out of 11) incorrectly believed that decreasing the temperature would cause the rate of product formation to increase. This misconception mirrors the one observed in Spring 2023, where GTAs assumed that shifting equilibrium toward products would also increase the rate of product formation, overlooking the role of temperature in affecting kinetic energy and collision frequency. In Question 5, 5 out of 11 GTAs believed that increasing the temperature in an exothermic reaction would slow down the forward rate. This again reflects a misapplication of Le Châtelier's Principle to reaction rate.

When asked about changes in concentration, similar conceptual misunderstandings emerged. In Question 2d, 6 GTAs (55%) believed that halving the volume would lead to a decrease in the concentration of the reactant side. Although the equilibrium shifts toward the product side in response to increased pressure, the concentration of all gases should increase due to the smaller volume. This reflects a recurring confusion between the amount of a substance (moles) and its concentration (moles per volume).

GTAs' understanding of the equilibrium constant in Fall 2023 was also very limited. Five GTAs selected "data insufficient" in Question 1c, and four GTAs selected it as well in Question 3b. It suggests a lack of understanding of what factors influence the equilibrium constant. In Question 3b, 3 GTAs believed that removing a reactant would cause the equilibrium constant to decrease. This response reveals a common misconception that shifting equilibrium backward lowers the value of K, despite temperature being the only factor that affects it. Lastly, in Question 4, no GTA answered correctly. This item required students to recognize that the equilibrium constant and mathematical calculation is needed to determine the mass of CO at the new equilibrium. Selecting a specific change in mass indicates a lack of understanding of how equilibrium problems are solved quantitatively.

Table 4-14 summarized the misconceptions identified in the second section of the CEDT from Fall 2023 pre-assessment.

Table 4-14 Summary of Misconceptions Identified in the Second Section of the CEDT (Fall 2023 Pre-Assessment)

Question(s)	Misconception	Percentages
Q1a	Belief that lowering temperature does not shift an exothermic equilibrium	27%
Q3a	Belief that removing one reactant causes passive decrease in the other	36%
Q1b, Q5	Misapplication of Le Châtelier’s Principle to predict rate change	55%, 45%
Q2d	Confusion between amount (moles) and concentration	55%
Q3b	Belief that removing a reactant alters the value of the equilibrium constant	36%
Q4	Belief that changes in mass can be determined without the equilibrium constant or concentrations	100%

4.2 GTAs’ Misconceptions Identified from Laboratory Observations in Spring 2023 and Fall 2023

Following the administration of the pre-assessment, GTAs led Lab 9: Reversible Reactions in their respective lab sections. This lab explores the concept of chemical equilibrium through two classic experiments: the chromate/dichromate ion equilibrium and the temperature-dependent equilibrium of cobalt complexes.

In the first experiment, $2CrO_4^{2-} + 2H^+ \rightleftharpoons Cr_2O_7^{2-} + H_2O$, students examine the effects of adding acids and bases to a solution of chromate ions. Observable color changes between yellow (CrO_4^{2-}) and orange ($Cr_2O_7^{2-}$) visually illustrate how changes in concentration shift the position of equilibrium.

The second experiment involves the equilibrium $CoCl_2(H_2O)_2 + 4H_2O \rightleftharpoons Co(H_2O)_6^{2+} + 2Cl^-$. Cobalt(II) chloride is used to explore the temperature-induced transition between blue tetrahedral complexes ($CoCl_2 \cdot (H_2O)_2$) and pink octahedral complexes ($Co(H_2O)_6^{2+}$).

These two experiments demonstrate how external factors, such as the concentration of reactants/products and temperature, influence chemical equilibria, linking macroscopic observations, such as color changes, to underlying molecular dynamics.

In theory, GTAs are expected to spend 10–15 minutes at the beginning of the lab introducing the purpose of the lab, key chemistry concepts, and important safety or procedural instructions, such as the proper use of a hot plate. In Spring 2023, GTAs were not provided with any supplementary instructional materials. In contrast, during Fall 2023, the department provided optional slides for each lab session, which GTAs could choose whether or not to use.

To evaluate the effectiveness of this instructional period, lab observations were conducted to document how GTAs communicated the principles of chemical equilibrium to students. The observations aimed to identify whether GTAs unintentionally introduced any misconceptions during their explanations or demonstrations.

4.2.1 Laboratory Observations in Spring 2023

In Spring 2023, 7 out of the 10 teaching assistants (TAs) who completed the pre-assessment granted permission for their Lab 9 sessions to be observed. Detailed notes were recorded during each observation. For consistency, I use the same identifiers (e.g., TA1, TA2) as in the previous sections to refer to the corresponding participants.

- **<u>Spring 2023 Instructional Observation #1:</u>**

TA3 arrived in the lab room 20 minutes early. After checking student drawers, TA3 wrote down the key points on the blackboard before class began. At the top, TA3 wrote the title "Reversible Reactions," followed by a general equation:

$$A + B \rightleftharpoons C + D$$

Underneath, three main factors affecting equilibrium were listed:

1. Adding/removing reactants or products
2. Temperature
3. pH

When class began, TA3 introduced the concept of reversible reactions. TA3 explained that these are reactions in which reactants convert to products and products return to reactants simultaneously. To illustrate this idea, TA3 pointed to the double-sided arrow in the equation, emphasizing that it means reversibility.

Without mentioning the concept of equilibrium, TA3 transitioned to the first factor influencing "reversible reactions": the addition or removal of reactants or products. Using clear and straightforward language, TA3 explained, "If we add more A, the reaction will shift to produce more products, C and D. Similarly, if we add more C or D, they will react with each other to generate more A and B. Eventually, the reaction will reach what we call 'equilibrium.'"

Next, TA3 moved to the second factor, temperature, which was described as a force that could "control" reversible reactions. TA3 began with an introduction to collision theory, explaining how higher temperatures cause molecules to become "more excited" and move faster. Building on this, TA3 defined exothermic and endothermic reactions, and then explained, "If you add heat to an exothermic reaction, the system will shift to oppose the change, reducing product formation. Conversely, for an endothermic reaction, adding heat drives the reaction forward to produce more products."

Finally, TA3 addressed the third factor, pH, relating it as a subcategory of the first factor: the addition or removal of reactants or products. TA3 referenced the reaction from the first experiment:

$$2CrO_4^{2-} + 2H^+ \rightleftharpoons Cr_2O_7^{2-} + H_2O$$

To engage the class, TA3 posed a question: "What happens if we add more acid to this reaction?" Only one student raised their hand and provided the correct answer. TA3 expanded on the explanation, saying, "When you add acid, you're adding more H^+, which increases the reactants. This causes the reaction to shift to the right, producing more products. On the other hand, if you add a base, it removes H^+. Now, there's more product, so the system shifts back to the left to regenerate the reactants."

TA3 wrapped up the lecture and then instructed students to begin the experiment.

Reflection:

TA3 successfully communicated key factors affecting chemical equilibrium. The factor "pressure" was substituted with "pH," which, although not covering all standard factors, directly aligned with the specific laboratory experiments. TA3 did not define what chemical equilibrium is. While no clear misconceptions were introduced, the absence of a definition might have limited students' understanding of the topic as a whole.

- **Spring 2023 Instructional Observation #2:**

TA6 started the class by introducing the observer (me) and emphasizing that if any student did not wish to be observed, they could sit near the rear sink. TA6 then opened the presentation with a probing question: "Can someone define to me what's equilibrium?"

Student A answered, "The chemical equation balances out. It's no longer exchanging ions and protons back and forth."

Student B said, "It's when the products and reactants aren't changing anymore, and the reaction is considered complete because there's no additional products or reactants being formed."

TA6 first appreciated the students' participation, then mentioned that stoichiometry is important for a reaction to happen, and maintaining stoichiometric ratios is necessary for a complete reaction. TA6 then stated that "equilibrium comes here as a continuation of stoichiometry."

After that, TA6 explained that equilibrium is a state where the reaction has occurred, and nothing is leaving the system. TA6 briefly mentioned the idea of "dynamic equilibrium" and "closed dynamic equilibrium," adding that students would learn more about these concepts in lecture class later on.

Next, TA6 brought up that there are certain changes or "stress" that can affect equilibrium in different ways. On the blackboard, TA6 wrote four terms: "concentration," "pressure," "heat," and "catalysts," along with the equation, $A + B \rightarrow C + D$.

TA6 explained that Le Châtelier's Principle tells us whenever a stress is applied to the system, "a shift will happen to fix it." For example: "When we have more reactants, we need to have more products to equate this change. If we have less products, it means reactants need to react more to produce for that." TA6 also repeated the idea of a "closed dynamic system," and stressed that nothing can leave the system. Therefore, when a change happens, something else must adjust to keep it balanced.

TA6 then asked students what the double-sided arrow means. After a student responded, TA6 acknowledged the answer and added that the double arrow means both the forward and reverse reactions occur at the same rate constant.

After that, TA6 connected the discussion to the lab experiments. TA6 asked, “How can you tell when we have an equilibrium change?” One student answered, “You could tell an equilibrium change because you’ll end up getting more of either side.” TA6 followed up: “How do you know you have more products?” Students responded with answers like color and heat. TA6 acknowledged the color response but stated that heat might not apply in all cases, since you often need to add a large amount of heat to observe a change such as vapor. However, color is something that can always be used to detect a shift. TA6 referred to the second experiment and explained that the reactants are blue, and the products are pink, and students will be able to observe the equilibrium shift based on the color change.

Then TA6 returned to teaching how to apply Le Châtelier’s Principle. Pointing to the blackboard, TA6 asked, “If we add more A, how would the equilibrium shift?” Students answered, “Shift to the right.” TA6 added, “Because you have more reactant, you basically need to produce more products. So, equilibrium will shift right.”

TA6 then brought up the second factor: pressure. TA6 used P = 1/V to illustrate that pressure and volume are inversely proportional. “Higher pressure means lower volume,” TA6 said. Then TA6 asked, “When we decrease pressure, how will the equilibrium shift?” A student answered, “It would shift to the side that has less moles.” TA6 thanked the student and added that decreasing pressure increases volume. To deal with this change, equilibrium would shift to the side with less moles. TA6 also reminded students to count the number of moles of reactants and products only for gases, not aqueous substances.

After that, TA6 discussed the effect of heat. Students were told that in an exothermic reaction, heat is on the product side; for an endothermic reaction, heat is on the reactant side. TA6 then asked, “If we increase the temperature for an exothermic reaction, how will the equilibrium shift?” One student answered correctly. TA6 explained that increasing temperature makes the heat on the product side “more massive,” and since the system is mainly closed, the equilibrium shifts to the left to deal with the excess heat.

Then TA6 moved on to the last factor: catalyst. TA6 specifically pointed out that this is a common misconception. TA6 explained to the class, “When we add a catalyst, the catalyst does not really affect the equilibrium. It only affects the rate of equilibrium by speeding it up. This is a reversible reaction, which means that the rate of the forward reaction is equal to the rate of the reverse reaction. So, whenever you add a catalyst, it's changing both rates, not one.”

At this point, TA6 wrapped up the teaching portion and shifted the focus to the lab manual. TA6 went through the basic procedures by reading through the lab manual instructions to students. Before finishing, TA6 asked students to apply what they had just learned to the first experiment:

$$2CrO_4^{2-} + 2H^+ \rightleftharpoons Cr_2O_7^{2-} + H_2O$$

TA6 asked, “If we add sulfuric acid to this reaction, how will the equilibrium shift?” The class was silent. TA6 explained that adding sulfuric acid increases H^+, which increases the concentration on the reactant side. Therefore, the equilibrium would shift to the right, toward the products. After this explanation, TA6 let the students begin the experiment.

Reflection:

TA6 spent a significant amount of time explaining the concept of chemical equilibrium, which showed a strong sense of responsibility and dedication. TA6 covered three common factors that affect equilibrium and also mentioned the effect of catalysts. In addition, TA6 demonstrated solid pedagogical skills by asking probing questions and engaging students throughout the session. However, several misconceptions were identified during the presentation.

First, when TA6 asked students to define equilibrium, Student A responded, "It's no longer exchanging ions and protons," and Student B said, "No additional products or reactants [are] being formed." Both responses suggest a common misconception that equilibrium is a static state. However, TA6 only acknowledged the participation and did not comment on or clarify the students' answers.

Second, TA6 described equilibrium as a state where the reaction has occurred and "nothing is leaving the system." This definition is incorrect and could reinforce the misunderstanding that equilibrium is a complete and static state rather than a dynamic balance between forward and reverse reactions.

Third, TA6 stated that the double arrow means both the forward and reverse reactions occur at the same rate constant. Additionally, TA6 said, "This is a reversible reaction, which means that the rate of the forward reaction is equal to the rate of the reverse reaction." This reflects a misconception. A reversible reaction (equation) does not necessarily mean that the system is at equilibrium. The equal rate of forward and reverse reactions only applies once equilibrium has been reached, not just because the reaction is reversible.

Later, TA6 said that heat might not apply in all cases, since a large amount of heat is often needed to observe a change such as vapor. While this may have been intended to ask for macroscopic signs of equilibrium shifts, the statement could imply that heat does not influence all equilibria. In fact, temperature changes always affect the equilibrium position of a system, even if the macroscopic changes are not always easily observable.

Lastly, TA6 said that decreasing pressure increases volume, and that equilibrium would shift to the side with less moles. This is incorrect. According to Le Châtelier’s Principle, a decrease in pressure (increase in volume) shifts the equilibrium to the side with more moles of gas.

- **Spring 2023 Instructional Observation #3:**

TA8 began the presentation using self-prepared slides. TA8 first told students that the day's experiment would focus on reversible reactions and would require “heavy observations.” TA8 then moved to the second slide, which displayed the definition of chemical equilibrium and Le Châtelier’s Principle.

TA8 started by introducing the concept of a reversible reaction, explaining that it is a reaction that does not go to completion. When reactants form some products, those products covert back to reactants simultaneously. TA8 further explained, “Chemical equilibrium is established when the forward and backward reactions have become equal to one another.”

Next, TA8 introduced Le Châtelier’s Principle, stating, “Le Châtelier's Principle describes three factors that can disturb equilibrium and predicts how a reversible reaction shifts to counteract these changes and restore balance.”

The first factor TA8 discussed was the addition/removal of reactants/products. TA8 used a weight balance analogy and physical gestures to help students visualize the concept. Students were asked to imagine a balance with equal weights on both sides. Then, TA8 said, “If a little more weight is added to the left side,” (while slightly lowering the left hand to demonstrate), “that side becomes heavier, causing the balance to tilt downward (to the left).”

TA8 then moved on to the second factor: changes in concentration due to volume or pressure changes. However, TA8 mentioned that this factor would not be explored in detail since it was not part of the day’s experiment

The third factor discussed was temperature. TA8 explained that there are two types of reactions: exothermic and endothermic and displayed the next slide, which listed two chemical equations:

$$2N_2 + 3H_2 \rightleftharpoons 2NH_3 + heat\ (exothermic)$$

$$N_2O_4 + heat \rightleftharpoons 2NO_2\ (endothermic)$$

Pointing to the exothermic reaction between nitrogen and hydrogen gas, TA8 explained, “It’s gonna shift to the product side when you remove the heat,” and “Adding heat will push it to the reactant side because the equation wants to go away from the heat side.”

Finally, TA8 told students they would be adding different solutions to observe how equilibrium can be affected.

Reflection:

TA8 delivered a well-structured lecture supported by self-prepared slides. TA8 also used analogies, such as a weight balance, to help students visualize how equilibrium shifts. The overall flow of the presentation was clear. However, a few misconceptions or unclear explanations were noted.

First, TA8 defined equilibrium as the point where the forward and backward reactions "have become equal to one another." While this is close, the phrasing is vague. It does not specify what becomes equal at equilibrium. Is it the concentration? The rate? Or something else? To avoid confusion, it is recommended that GTAs use precise language when defining key terms like chemical equilibrium.

Second, in the weight balance analogy, TA8 stated that adding more weight causes the balance to tilt toward the added side. While this is a helpful visual, it could be misinterpreted. According to Le Châtelier's Principle, a system typically shifts away from the added stress. The analogy itself is useful, but it would benefit from clearer explanation to align more accurately with the scientific concept.

- **Spring 2023 Instructional Observation #4:**

TA9 arrived in the lab room approximately ten minutes early. After opening students' drawers, TA9 projected self-made slides onto the screen. The presentation began with a brief introduction: “Today’s lab is about reversible reactions and chemical equilibrium. We are going to see how the reactants go to products, as well as how the products go back to the reactants.” TA9 then stated, “All you need to know today is Le Châtelier’s principle.”

On the next slide, a general equation, $A + 2B \rightleftharpoons C + D$, was displayed alongside the definition of Le Châtelier’s Principle: “If a chemical reaction is at equilibrium and experiences a change in pressure, temperature, or concentration of products or reactants, the equilibrium shifts in the opposite direction to offset the change.”

Pointing at the equation on the slide, TA9 explained, “If we add more A or B, the equilibrium will shift to the right to make more C and D. And if you are taking away A and B, it would be the opposite, where C and D shift left to compensate for this change.” TA9 continued, “When the equation reaches equilibrium, the concentration of A and B are the same. At this time, if you add more C and D, the equilibrium will shift left to make more A and B.”

Next, TA9 moved to a slide titled “Endo/Exothermic Reactions.” The slide showed two equations:

$$Endothermic: Reactants + heat \rightarrow Products$$

$$Exothermic: Reactants \rightarrow heat + Products$$

TA9 explained: “An exothermic reaction releases heat, so the reaction gets hotter. An endothermic reaction absorbs heat, so it gets cooler.” Then TA9 added, “Adding heat for an endothermic reaction would make the equation shift to the products. Similarly, adding heat for an exothermic reaction will make it shift to the reactants."

TA9 did not mention pressure as a factor influencing equilibrium. Instead, the focus shifted directly to the chemical reactions used in the experiment. TA9 displayed an equation, $CrO_4^{2-} + H^+ \rightleftharpoons Cr_2O_7^{2-} + H_2O.$ TA9 lectured that adding H_2SO_4 is equivalent to adding H^+, which shifts the equilibrium to the product side. On the other hand, adding NaOH introduces OH^-, which combines with H^+ to form H_2O. By removing H^+ or adding H_2O, the equilibrium shifts back to the reactants. After this, TA9 walked students through the steps for the second reaction in the lab and then let students start the experiment.

Reflection:

TA9 delivered a clear and structured overview of chemical equilibrium and Le Châtelier's Principle. Key concepts such as the effects of concentration and temperature on equilibrium were introduced with appropriate examples.

However, TA9 stated, "When the equation reaches equilibrium, the concentration of A and B are the same," which reflects a common misconception. At equilibrium, the rates of the forward and reverse reactions are equal, not necessarily the concentrations of reactants and products.

Additionally, although Le Châtelier's Principle was explained in detail, TA9 did not clearly define the terms "reversible reaction" or "chemical equilibrium," which may limit students' foundational understanding.

- **Spring 2023 Instructional Observation #5, #6 and #7:**

TA4 arrived at the laboratory on time. After opening all the student drawers, TA4 directed the students to review the lab manual. TA4 emphasized that the focus of the lab would be on observing color changes. TA4 said, “For Part 1, after adding sulfuric acid or sodium hydroxide into the test tube, is there any color change? Or any bubbles formed? That’s what you need to look for.” For Part 2, TA4 clearly explained the steps by drawing four test tubes on the blackboard and describing the conditions that would be applied to each one. After going over the experimental procedures, TA4 allowed students to begin the lab.

TA5 arrived at the lab 10 minutes early, opened the drawers for students, and refilled the reagent bottles. When class began, TA5 told students to follow the instructions in the lab manual and to add the corresponding solutions until they observed a color change. TA5 then allowed the students to begin the lab.

TA7 reviewed the experimental procedures with students. TA7 explained that there would be two chemical reactions in each part of the experiment. The chemical equations could be found in the lab manual. TA7 also suggested using a white scratch sheet as a background to help observe color changes. After this explanation, TA7 let the students begin the lab.

Reflection:

TA4, TA5, and TA7 took a similar approach by only reviewing the experimental procedures with students. None of them addressed or explained the concept of chemical equilibrium during their instruction.

Summary of Findings from Laboratory Observations in Spring 2023:

Out of the seven GTAs observed in Spring 2023, three (TA4, TA5, and TA7) did not introduce or discuss the concept of chemical equilibrium at all. The remaining four GTAs (TA3, TA6, TA8, and TA9) introduced the concept of reversible reactions and Le Châtelier's Principle to varying degrees. While some presentations were clear and well-structured, several misconceptions or vague explanations were identified (see ***Table 4-15***). These included unclear definitions of equilibrium, confusion between reversible reactions and equilibrium, incorrect interpretation of pressure and temperature effects, and ambiguous use of analogies.

Table 4-15 Misconceptions Identified During Laboratory Observations in Spring 2023

Misconception	GTA(s)
Equilibrium is a state where "nothing is leaving the system"	TA6
Double arrow means equilibrium or equal forward and reverse rate constants	TA6
Decreasing pressure shifts equilibrium to the side with fewer moles of gases	TA6
Unclear definition of equilibrium (vague phrasing)	TA8
Equilibrium means equal concentrations of A and B	TA9

4.2.2 Laboratory Observations in Fall 2023

In Fall 2023, 7 out of the 11 teaching assistants (TAs) who completed the pre-assessment granted permission for their Lab 9 sessions to be observed. Detailed notes were recorded during each observation. For consistency, I use the same identifiers (e.g., TA1*, TA2*) as in the previous sections to refer to the corresponding participants.

- **Fall 2023 Instructional Observation #1:**

TA1* arrived in class and began writing the following notes on the blackboard:

"Reversible Changes

Objective: observe effects of acid/base/temp on reversible rxns

$A + 2B \rightleftharpoons C + D$"

Once students had settled, TA1* started the presentation by introducing the concept of reversible reactions, explaining: "Reversible reactions are forward and reverse reactions happening simultaneously." TA1* then stated that the objective of the day's lab was to observe how equilibrium shifts in response to various changes applied to reversible reactions.

Next, TA1* directed students' attention to the equation written on the board and posed a question: "How will the equilibrium move if we add some A or B?" A student responded, "It will move to the right." TA1* acknowledged the answer and followed up: "What if I add some C or D?" The same student replied, "It will move to the left side." TA1* nodded.

TA1* then introduced the effect of temperature, stating that for an exothermic reaction, lower temperatures favor the forward reaction, and higher temperatures favor the reverse.

After that, TA1* asked students to turn to the second reaction in the lab manual. TA1* briefly explained that a complex ion typically has a metal as the central atom bonded with ligands, such as water molecules or chloride ions. TA1* also pointed out that in the second experiment, students would heat and cool a solution to determine whether the reaction is exothermic or endothermic.

Following this brief introduction, TA1* released students to begin the experiment.

Reflection:

TA1* gave a very brief introduction to reversible reactions and covered two factors from Le Châtelier's Principle: the addition/removal of reactants or products and temperature. No misconceptions were identified in the presentation. However, TA1* did not define chemical equilibrium before discussing Le Châtelier's Principle.

- **Fall 2023 Instructional Observation #2:**

As students settled in, TA2* began the presentation by introducing that the day's experiment would focus on reversible reactions.

Then, TA2* raised both hands in front of the chest and explained, "Reversible reactions are reactions that can go in both directions and nothing runs out. If my left-hand side gets smaller, the reaction will move backward. If my right-hand side gets smaller, the reaction will move forward." TA2* further clarified, "When the left-hand side gets smaller, that means the right-hand side is bigger than the left-hand side. Now, the right-hand side is going to become the reactants."

TA2* then directed students to look at the equation in the lab manual: $2CrO_4^{2-} + 2H^+ \rightleftharpoons Cr_2O_7^{2-} + H_2O$. TA2* explained that adding H^+ would shift the reaction forward, while adding OH^- would shift it backward.

To further illustrate this factor, TA2* drew a beaker on the blackboard with $Cr_2O_7^{2-}$, CrO_4^{2-} and H_2O inside. TA2* wrote that, initially, the ratio of CrO_4^{2-} to $Cr_2O_7^{2-}$ was 20:10. After adding H^+, the ratio would change to 10:20, indicating a shift toward the products. TA2* concluded by saying that this example was meant to help students better understand how the equilibrium would shift in the experiment.

After the explanation, TA2* allowed students to begin the lab.

Reflection:

TA2* gave a clear definition of reversible reactions but did not define chemical equilibrium. While explaining Le Châtelier's Principle, TA2* focused solely on the factor of adding or removing reactants and products. The use of hand gestures to demonstrate equilibrium shifts was engaging and effective.

However, the explanation involving the ratio of reactants to products was unclear. If the ratio changes from 20:10 to 10:20, it doesn't clearly indicate how this reflects the direction of the equilibrium shift, especially without additional context. This part may have caused confusion for students.

- **Fall 2023 Instructional Observation #3:**

After opening all the drawers, TA3* began the presentation by asking students to look at their lab manuals. TA3* introduced that today's lab was about reversible reactions and explained, "Reversible reactions are two reactions, forward and reverse, happening simultaneously. Neither reaction is complete.

Chemical equilibrium is reached when the concentration of each reactant and product remains constant."

To further explain the concept, TA3* used an analogy involving a bucket of water: "If you have a bucket of water and the water is about this high" (with a hand gesture indicating the height), "and I start to add water from the top and then I cut a hole at the bottom of the bucket. If the system is at equilibrium, the level of the water won't change." TA3* continued, "But sometimes the two flow rates are not equal. If I'm adding water at 6 L/min from the top, but it's flowing out pretty quick at 10 L/min, then you'll see the water level in the bucket keeps lowering down. The reactants and the products are like the same, going back and forth."

TA3* then directed students to the lab manual and clarified that the first experiment involved observing changes in chromate solution. TA3* also walked students through the second experiment, where they would perform a series of tests to determine which side of the reaction, they were on based on the color of the solution. Before concluding, TA3* revisited the earlier analogy by saying, "Just think about the flow in one direction versus the flow in the other direction."

After this explanation, TA3* let students begin the lab.

Reflection:

TA3* did a very good job introducing the definitions of reversible reactions and chemical equilibrium. The analogy of a water bucket was effective in illustrating the idea of dynamic equilibrium, particularly the concept that equilibrium involves continuous forward and reverse processes with no net change overall. However, when TA3* extended the analogy to describe unequal flow rates, the system was no longer at equilibrium. While this showed that equilibrium could be disturbed, it didn't connect to the idea of how the system would respond or shift to restore balance. As a result, the example didn't really illustrate Le Châtelier's Principle.

- **<u>Fall 2023 Instructional Observation #4:</u>**

After arriving at the lab room, TA4* opened the students' lab drawers and checked the solutions in the fume hood. TA4* then wrote the following on the blackboard:

Blue: $COCl_2 \cdot (H_2O)_2$	*Endo*	*Exo*
Pink: $Co(H_2O_6)^{2+}$	*Heat Absorbed,* $\Delta H>0$	*Heat Released,* $\Delta H<0$

Once all students arrived, TA4* asked them to take a picture of the blackboard and just begin the experiment.

<u>Reflection:</u>

TA4* didn't provide any instructional introduction. There was also a typo on the blackboard. The formula for the pink complex should be written as $Co(H_2O)_6^{2+}$.

- **<u>Fall 2023 Instructional Observation #5:</u>**

TA6* arrived at the lab about five minutes early, opened the drawers for students, and prepared for class by projecting the slides provided by the general chemistry team.

Once students settled in, TA6* began the presentation by saying, "In this lab, we're working with reversible reactions, where reactants turn into products and products turn back into reactants at the same time. We can change conditions and create favorability for projection over the other." TA6* then displayed a slide showing two chemical equations:

$$2CrO_4^{2-} + 2H^+ \rightleftharpoons Cr_2O_7^{2-} + H_2O$$

$$CoCl_2(H_2O)_2 + 4H_2O \rightleftharpoons Co(H_2O)_6^{2+} + 2Cl^-$$

Directing students to the first equation, TA6* introduced that the chromate ion can react with itself in an acidic solution to form dichromate, which has a yellow color. TA6* continued, "If you change the conditions, make the solution less acidic or reduce the hydrogen ion concentration, you'll start to see it shift back into the chromate ion."

Turning to the second equation, TA6* said, "Cobalt chloride can form a complex with two water molecules as ligands. If you add more water, you can get cobalt hexahydrate with two chloride counterions. So instead of the chloride acting as ligands, they become free ions."

At this point, TA6* asked whether students were familiar with Le Châtelier's Principle. Some students nodded, while others shook their heads. TA6* explained, "If you increase the reactants on one side, it pushes the reaction to the other side. If you decrease the reactants on one side, it pulls into it." TA6* added, "If you add hydronium or remove water, you are pushing the system this way (gesturing to the right). If you add water and reduce hydronium, it pushes it left."

TA6* then pointed to the second equation and said the same principle applied: adding water shifts the equilibrium to the right, while adding chloride ions shifts it to the left.

TA6* then pointed out an error in the PowerPoint slide. The experimental procedures listed on the slide were from the previous lab. As a result, TA6* provided a brief overview of the procedures. TA6* also gave a specific caution: adding too much water to the cobalt complex may prevent further color changes from occurring. Students were advised to add just enough water to initiate the visible shift. After this explanation, TA6* allowed students to begin the lab.

Reflection:

TA6* gave a strong introduction to the lab and clearly defined the concept of reversible reactions. However, the concept of chemical equilibrium was not explicitly defined. Regarding Le Châtelier's Principle, TA6* only addressed one factor: the addition or removal of reactants or products.

One minor inaccuracy was noted. TA6* stated that the dichromate ion is yellow, when it is actually orange.

- **Fall 2023 Instructional Observation #6:**

TA8* arrived at the lab 10 minutes early and wrote two equations on the blackboard:

$$A + B \rightleftharpoons C + D$$

$$2CrO_4^{2-} + 2H^+ \rightleftharpoons Cr_2O_7^{2-} + H_2O$$

As students settled in, TA8* began the presentation by introducing the concept of reversible reactions. TA8* explained, "A reversible reaction is a reaction that can go in one direction and then go back. Suppose we have the reactants A plus B," (while pointing at the first equation on the board). "This arrow represents the forward direction, and this arrow is for the backward direction."

TA8* then explained that in the forward reaction, A and B are the reactants and C and D are the products. In the backward reaction, C and D become the reactants and produce A and B. TA8* continued, "So in this reaction, a state exists where A, B, C, and D all coexist. Those states are known as equilibrium."

TA8* repeated this definition once more: "So reversible reactions have an equilibrium state where all four substances exist together."

Next, TA8* directed students' attention to the second equation on the board and stated that this reaction was also reversible in nature. TA8* said, "When we add hydrogen to 'Cr O four two minus' (CrO_4^{2-}), it gives us 'Cr two O seven two minus' ($Cr_2O_7^{2-}$) and water. All these four things will coexist." TA8* also explained that in the experiment, sulfuric acid would be the source of H^+, and students should observe a color change from yellow to orange when it is added.

TA8* then moved on to discuss the second experiment. Students were instructed to add water to the cobalt solution and observe whether the color changes to pink. TA8* emphasized that once the solution turned pink, they should stop adding water. Only the minimum amount of water needed to initiate the color change should be used.

After the explanation, TA8* let the students begin the lab.

Reflection:

TA8* appeared to focus more on the experimental procedures than on explaining the underlying chemical equilibrium concepts.

When defining reversible reactions, TA8* explained, “A reversible reaction is a reaction that can go in one direction and then go back.” This definition did not emphasize that the forward and reverse reactions occur simultaneously, which may lead to the misconception that reversible reactions behave like oscillating reactions. Moreover, the statement that "reversible reactions have an equilibrium state where all four substances exist together" also conveyed a misconception. This phrasing may lead students to believe that equilibrium simply means all components are present, rather than understanding equilibrium as a dynamic state where the rates of the forward and reverse reactions are equal.

In addition, TA8* did not address Le Châtelier’s Principle at all. While TA8* mentioned that adding H^+ would result in the formation of the dichromate ion, students may have interpreted the change as a one-way process rather than a reversible response governed by equilibrium shifts.

- **Fall 2023 Instructional Observation #7:**

TA9* began the presentation by stating that they would be working on reversible reactions and Le Châtelier's Principle in that day's lab. TA9* asked, "What do you mean by reversible reaction?" After receiving no response from students, TA9* continued, "A reversible reaction is a reaction where reactants turn to products and products turn to reactants simultaneously. And Le Châtelier's principle states if any change is added to the system, the system will move against the change."

TA9* then guided students to the equation provided in the lab manual: $2CrO_4^{2-} + 2H^+ \rightleftharpoons Cr_2O_7^{2-} + H_2O$. TA9* asked, "What would happen if we add H^+?" One student responded that the reaction would shift to the right. TA9* followed up by asking, "What would happen if we add OH^-?" After receiving no response, TA9* explained that OH^- would combine with H^+ to form water. The removal of H^+ would decrease its concentration, causing the reaction to shift to the left.

Next, TA9* walked through the procedures for the second experiment. After this, TA9* allowed students to begin the lab.

Reflection:

TA9* gave a clear introduction to the experimental procedures along with some related concepts in chemical equilibrium. Although TA9* provided definitions of reversible reactions and Le Châtelier's Principle, the term "equilibrium" was not clearly introduced or defined during the presentation.

Summary of Findings from Laboratory Observations in Fall 2023:

Compared to the GTAs observed in Spring 2023, those in Fall 2023 generally spent less time introducing chemical equilibrium concepts to students. Most presentations lasted approximately 3 to 5 minutes and focused more on laboratory procedures than on chemical equilibrium knowledge. Although GTAs were provided with instructional slides prepared by the general chemistry team, only one GTA (TA6*) used them.

During this semester, TA4* did not provide any introduction to chemical equilibrium. All remaining GTAs defined reversible reactions; however, only two out of seven (TA3* and TA8*) also defined "chemical equilibrium" during their introductions. All GTAs except TA3*, TA4*, and TA8* attempted to introduce Le Châtelier's Principle, although the coverage was limited. Most GTAs only addressed the effect of adding or removing reactants or products.

One misconception was identified when TA8* stated that equilibrium simply means that all substances coexist.

TA3* used a water bucket analogy that was helpful initially but became confusing when unequal flow rates were introduced without connecting it to Le Châtelier's Principle.

Table 4-16 Misconceptions Identified During Laboratory Observations in Fall 2023

Misconception	GTA(s)
Defined a reversible reaction as one that goes forward and then back	TA8*
Defined equilibrium as the coexistence of all substances	TA8*
Used an inappropriate or confusing analogy	TA2*, TA3*

4.3 Impact of the Mini-Lecture: GTAs' Performance on the Post-Assessment in Spring 2023 and Fall 2023

In Spring 2023, ten GTAs completed both the pre- and post-assessments, with six of them attending the mini-lecture. In Fall 2023, eleven GTAs completed both assessments, and eight attended the mini-lecture. To evaluate the effectiveness of the mini-lecture, this section compares GTAs' performance on the pre- and post-assessments between those who participated in the mini-lecture and those who did not.

4.3.1 Comparison of Pre- and Post-Assessment Results in Spring 2023

In Spring 2023, four GTAs (TA1, TA2, TA8, and TA10) did not attend the mini-lecture and are labeled as non-attendees. The remaining six GTAs (TA3, TA4, TA5, TA6, TA7, and TA9) attended the mini-lecture and are referred to as attendees. ***Table 4-17*** presents the overall performance on the Chemical Equilibrium Diagnostic Test (CEDT) before and after the mini-lecture for both groups. The non-attendees had an average pre-assessment score of 7.50 (SD = 1.00) and a post-assessment mean of 9.00 (SD = 1.87), while the attendees had a mean pre-assessment score of 6.83 (SD = 1.47) and a post-assessment mean of 9.33 (SD = 1.51). These results suggest that both groups showed improvement. However, attendees started with a slightly lower pre-assessment score and achieved a marginally higher post-assessment score.

Table 4-17 Pre- and Post-Assessment Performance on the CEDT for GTAs in Spring 2023

	Non-Attendees (N=4)	Attendees (N=6)

	Mean	SD	Mean	SD
Pre-Assessment	7.50	1.00	6.83	1.47
Post-Assessment	9.00	1.87	9.33	1.51

After observing an improvement in performance on the CEDT before and after the mini-lecture, we became interested in one key question: "Did performance on the CEDT improve more for GTAs who attended the mini-lecture than for those who did not?" To explore this, a mixed ANOVA was conducted.

The results of Levene's test showed that the assumption of equal variances was met for both pre-assessment ($F(1, 8) = 0.976$, $p = 0.352$) and post-assessment scores ($F(1, 8) = 0.325$, $p = 0.584$) in both the non-attendee and attendee groups, indicating that the assumptions required for a parametric test were satisfied.

The interaction effect, which examines whether the change in performance scores differs between the two groups, is of central interest. This effect was found to be non-significant ($F(1, 8) = 0.63$, $p = 0.451$), suggesting that there is no evidence to support the idea that the increase in performance on the CEDT was influenced by the mini-lecture intervention.

Although the statistical test indicated that the mini-lecture did not significantly address GTAs' misconceptions or improve their performance on the CEDT, it is important to note that this study had a very small sample size in both the control and treatment groups. As a result, the study may be susceptible to a Type 2 error (false negative)[121], where the test fails to detect an effect when one truly exists. Given this possibility, we still wanted to examine GTAs’ responses to each question more closely.

In the following section, we will break down the first and second sections of the CEDT to see if there is any improvement that could suggest the mini-lecture had some effect in addressing GTAs' misconceptions.

4.3.1.1 Comparison of GTAs' Performance on the First Section of the CEDT (Spring 2023)

Using the same rubrics from Table 4-2 and Table 4-5, GTAs' responses to the first section of the post-assessment were evaluated and compared to their pre-assessment responses. ***Table 4-18*** presents the comparison of GTAs' performance on the first section of the CEDT between the pre- and post-assessments, separated by mini-lecture attendance.

For Question 1, none of the non-attendees revised or improved their definitions of the rate of reaction. For instance, TA8 wrote, "Rate of Rxn is a term used to explain the speed of reaction," in the pre-assessment and gave a nearly identical response in the post-assessment: "Rate of Rxn means the speed at which reactants are converted to products." Moreover, none of the non-attendees referenced the IUPAC definition in either assessment, even though this definition was explicitly introduced and discussed during the mini-lecture. Among the attendees, one TA (TA3) improved from an incorrect response in the pre-assessment to a correct one after the mini-lecture. While only TA7 used IUPAC-based phrasing in the pre-assessment, three GTAs (TA3, TA7, and TA9) incorporated the idea of "concentration change over time" in the post-assessment.

For Question 2, the pattern was similar. None of the non-attendees revised their incorrect reasoning. TA2 and TA10 continued to state that "increasing the temperature increases the reaction rate because the reaction is endothermic." On the other hand, TA6 and TA9 (attendees) corrected earlier misconceptions, such as "heat acts as a catalyst," and provided more accurate explanations involving kinetic energy. Notably, none of the attendees mentioned collision theory in their pre-assessment responses, but two GTAs (TA3 and TA7) applied it in their post-assessment. For instance, TA7 wrote: "According to the collision theory of chemical reactions, molecules must collide with proper energy and orientation to react. Increasing the temperature raises the number of effective collisions per second, increasing the reaction rate."

For Question 3, all GTAs selected the correct answer (Option B) on the post-assessment, regardless of attendance. However, in the open-ended responses, none of the GTAs explicitly recognized that concentration was not provided, even though most used stoichiometric relationships to justify their reasoning. This suggests a persistent gap in understanding the distinction between amount and concentration in reaction rate calculations.

Table 4-18 GTAs' Pre- and Post-Assessment Performance on Section 1 of the CEDT (Spring 2023), by Mini-Lecture Attendance

	Question 1		Question 2		Question 3	
	Pre	Post	Pre	Post	Pre	Post
Non-Attendees						
TA1	1	1	1	1	1	1
TA2	1	1	0	0	1	1
TA8	1	1	1	1	0	1
TA10	0	0	0	0	0	1
Overall Correct%	75%	75%	50%	50%	50%	100%
Attendees						
TA3	0	1	1	1	1	1
TA4	1	1	1	1	1	1

TA5	1	1	0	0	0	1
TA6	1	1	0	1	1	1
TA7	1	1	1	1	1	1
TA9	1	1	0	1	1	1
Overall Correct%	83%	100%	50%	83%	83%	100%

4.3.1.2 Comparison of GTAs' Performance on the Second Section of the CEDT (Spring 2023)

Table 4-19 presents a comparison of GTAs' performance on the second section of the CEDT during Spring 2023, categorized by mini-lecture attendance.

Overall, GTAs who attended the mini-lecture showed improvement on more questions than those who did not attend. Specifically, attendees improved in 7 out of the 11 questions, whereas non-attendees improved in only 3 questions. Notably, the attendees demonstrated significant improvements in questions relating to equilibrium shift (Q1a, Q2a, Q2c), relating reaction rate to equilibrium (Q1b, Q5), and understanding changes in concentration at equilibrium (Q2b).

In contrast, non-attendees exhibited limited improvement overall, with significant progress only observed in Q1a, Q5, and Q1c. Moreover, non-attendees maintained their initial performance levels on most questions, reflecting minimal to no change post-intervention.

These findings indicate that attendance at the mini-lecture positively impacted GTAs' understanding and performance on the CEDT, suggesting the effectiveness of the mini-lecture intervention in addressing misconceptions and reinforcing key concepts in chemical equilibrium.

Table 4-19 Comparison of GTAs' Performance on the Second Section of the CEDT (Spring 2023), by Mini-Lecture Attendance

Question	Non-Attendees			Attendees		
	Pre%	Post%	Diff	Pre%	Post%	Diff
Equilibrium Shift						
Q1a	25%	50%	25%	50%	67%	17%
Q2a	100%	100%	0%	67%	100%	33%
Q2c	100%	100%	0%	50%	83%	33%
Q3a	100%	100%	0%	83%	83%	0%
Relating Reaction Rate and Equilibrium						
Q1b	75%	75%	0%	50%	67%	17%
Q5	25%	75%	50%	50%	67%	17%
Changes in Concentration at Equilibrium						
Q2b	100%	100%	0%	50%	100%	50%
Q2d	0%	0%	0%	17%	0%	-17%
Equilibrium Constant Understanding						
Q1c	0%	25%	25%	0%	17%	17%
Q3b	50%	50%	0%	50%	67%	17%
Q4	0%	0%	0%	0%	0%	0%

Note: Pre% = the percentage of GTAs who answered the question correctly on the pre-assessment. Diff = the change in percentage from pre- to post-assessment (Post% - Pre%)

4.3.2 Comparison of Pre- and Post-Assessment Results in Fall 2023

In Fall 2023, three GTAs (TA4, TA9, TA11) did not attend the mini-lecture and are labeled as non-attendees. The remaining eight GTAs attended the mini-lecture and are referred to as attendees. ***Table 4-20*** presents the overall performance on the Chemical Equilibrium Diagnostic Test (CEDT) before and after the mini-lecture for both groups. The non-attendees had an average pre-assessment score of 6.67 (SD = 1.53) and a post-assessment mean of 7.33 (SD = 1.53), while the attendees had a mean pre-assessment score of 5.50 (SD = 1.93) and a post-assessment mean of 7.50 (SD = 2.73). These results indicate improvement in both groups, although attendees had a greater overall increase.

Table 4-20 Pre- and Post-Assessment Performance on the CEDT for GTAs in Fall 2023

	Non-Attendees (N=3)		Attendees (N=8)	
	Mean	SD	Mean	SD
Pre-Assessment	6.67	1.53	5.50	1.93
Post-Assessment	7.33	1.53	7.50	2.73

A mixed ANOVA was conducted to determine if the mini-lecture influenced changes in GTA performance from pre- to post-assessment. Levene's test confirmed equal variances for both pre-assessment ($F(1, 9) = 0.888$, $p = 0.371$) and post-assessment scores ($F(1, 9) = 1.199$, $p = 0.302$), indicating the assumptions required for parametric testing were met.

The primary focus of this analysis was the interaction effect, which examines whether the change in performance scores differs between the two groups. This effect was found to be non-significant ($F(1, 9) = 3.273$, $p = 0.104$), suggesting that there is no evidence to support the idea that the increase in performance on the CEDT was influenced by the mini-lecture intervention.

Similar to Spring 2023, the first and second sections of the CEDT were analyzed separately to identify potential improvements that could indicate the mini-lecture's effectiveness in addressing GTAs' misconceptions.

4.3.2.1 Comparison of GTAs' Performance on the First Section of the CEDT (Fall 2023)

Table 4-21 presents the comparison of GTAs' performance on the first section of the CEDT between the pre- and post-assessments, separated by mini-lecture attendance.

For Question 1, similar to findings in Spring 2023, none of the non-attendees showed improvements or revisions in their definitions of reaction rate. However, among attendees, TA8 improved from an incorrect response to a correct one after the mini-lecture. Additionally, no GTA initially used the phrase "concentration change over time" in the pre-assessment, but two GTAs (TA7 and TA8) introduced this terminology in their post-assessment responses. Specifically, TA8 provided the answer: "Δ*[C]/t or –*Δ*[A]/t, change in conc of product over time.*"

For Question 2, one non-attendee (TA4) revised their incorrect reasoning from "*The reaction is endothermic, and it needs heat, thus supplying heat will increase the rate of reaction*" to a correct explanation emphasizing kinetic energy and effective collisions. Among attendees, TA1 corrected their initial incorrect reasoning. Additionally, TA1 and TA7 did not utilize collision theory in their initial responses but applied it post-mini-lecture.

For Question 3, non-attendees maintained consistent responses from pre- to post-assessment. Among attendees, however, two additional GTAs selected the correct answer (Option B) in the post-assessment. Notably, two attendees used the IUPAC-style mathematical expression in their justifications, whereas none of the

GTAs had done so in the pre-assessment. Attendee TA1 wrote “$Rate = [Na_2S_2O_3] = \frac{1}{2}[S]$” and Attendee TA8 wrote “(*Yes,* $-\frac{\Delta[reactant]}{t}$ *or* $\frac{\Delta[product]}{t} \Longrightarrow$ *2 mol/min.*” Although they did not acknowledge the absence of concentration data, their use of the IUPAC expression still suggests the mini-lecture had some positive effect, as this concept was explicitly covered during the session.

Table 4-21 GTAs' Pre- and Post-Assessment Performance on Section 1 of the CEDT (Fall 2023), by Mini-Lecture Attendance

	Question 1		Question 2		Question 3	
	Pre	Post	Pre	Post	Pre	Post
Non-Attendees						
TA4	1	1	0	1	0	0
TA9	0	0	0	0	1	1
TA11	1	1	0	0	1	1
Overall Correct%	67%	67%	0%	33%	67%	67%
Attendees						
TA1	1	1	0	1	0	1
TA2	1	1	0	0	1	1
TA3	0	0	0	0	1	1
TA5	1	1	1	1	0	1
TA6	1	1	1	1	0	0
TA7	1	1	1	1	0	1
TA8	0	1	1	1	1	1
TA10	1	1	0	0	0	0
Overall Correct%	75%	88%	50%	63%	38%	75%

4.3.1.2 Comparison of GTAs' Performance on the Second Section of the CEDT (Fall 2023)

Table 4-22 compares GTAs' performance on the second section of the CEDT during Fall 2023 by mini-lecture attendance. Consistent with Spring 2023, attendees showed improvement in more questions (7 out of 11) compared to non-attendees (2 questions).

Both groups experienced declines in performance on certain questions, notably Q2b, which focused on concentration changes at equilibrium. These declines suggest persistent misconceptions that may require further targeted instructional interventions.

Table 4-22 Comparison of GTAs' Performance on the Second Section of the CEDT (Fall 2023), by Mini-Lecture Attendance

Question	Non-Attendees			Attendees		
	Pre%	Post%	Diff	Pre%	Post%	Diff
Equilibrium Shift						
Q1a	100%	100%	0%	38%	75%	38%
Q2a	67%	67%	0%	38%	63%	25%
Q2c	67%	67%	0%	50%	75%	25%
Q3a	67%	67%	0%	38%	75%	38%
Relating Reaction Rate and Equilibrium						
Q1b	0%	33%	33%	25%	50%	25%
Q5	0%	33%	33%	38%	50%	13%
Changes in Concentration at Equilibrium						
Q2b	100%	67%	-33%	88%	63%	-25%
Q2d	33%	33%	0%	25%	13%	-13%
Equilibrium Constant Understanding						
Q1c	33%	33%	0%	25%	25%	0%
Q3b	67%	67%	0%	13%	38%	25%
Q4	0%	0%	0%	0%	0%	0%

Note: Pre% = the percentage of GTAs who answered the question correctly on the pre-assessment. Diff = the change in percentage from pre- to post-assessment (Post% - Pre%)

4.4 GTAs' Perceptions of the Mini-Lecture and Recommendations for Additional Support

To better understand the impact of the mini-lecture intervention, follow-up interviews were conducted with four graduate teaching assistants: two from the Spring 2023 cohort and two from the Fall 2023 cohort. Pseudonyms were assigned to theses four interviewees as Amy, Bob, Caleb, and Daisy. These names were chosen arbitrarily and do not reflect the participants' actual genders.

This section presents their feedback on the usefulness of the mini-lecture in clarifying key concepts and its relevance to their teaching. GTAs also discussed the challenges they encountered and offered suggestions for additional support that could enhance their confidence and effectiveness in teaching general chemistry. During the interviews, I aimed to create an open environment that encouraged TAs to share their experiences as general chemistry instructors and to reflect on how the department could better support their teaching efforts.

The interview transcripts were carefully reviewed and analyzed using thematic analysis to uncover common patterns and insights related to GTAs' perceptions of the mini-lecture and their overall teaching experiences. This process led to the identification of three major themes, each including a set of related codes. These themes and their corresponding codes are presented in the thematic matrix (see ***Table 4-23***).

Table 4-23 Identified Themes and Codes from Follow-Up Interviews with GTAs

Theme	Code(s)
TA Experience at OU	TA enjoyment & satisfaction
	Differences from previous institutions
	TA-Student relationship
	Challenges faced by TAs
Benefits of Diagnostic Test & Mini-Lecture	Identifying misconceptions & knowledge gaps
	Clarifying concepts and enhancing confidence
Future Support for TAs	Condensed manual/pamphlet
	Improved training frequency & methods

	Linking lab to lecture explicitly
	Departmental communication & clarity

4.4.1 GTAs' Teaching Experience at OU

Participants reported generally positive feelings about their teaching experiences but also expressed several concerns and complaints. Three interviewees expressed that teaching was a fulfilling part of their academic journey. Amy shared, "*I like being a TA here. I like interacting with students and helping them when they have questions.*" Similarly, Bob stated, "*I really like teaching. In fact, it's probably my favorite part of this whole thing,*" while Daisy affirmed simply, "*Yeah, I enjoy it.*"

Participants also shared the differences between their experiences as TAs at their undergraduate institutions and at OU. Bob explained, "*I didn't expect to have such a leadership role, like, taking over my own lab, because in my other school, TAs, all they did was kind of assisting the lecturer. You know, they (TAs in my other school) didn't really run their own lab or host their own stuff.*" Similarly, Caleb noted, "*In my undergrad, the professor was the main teacher during lab, and then I was kind of there to assist them.*" Daisy added that, in their undergraduate institution, students entering general chemistry typically had a strong foundation in the subject due to extensive high school preparation. In contrast, at OU, students come from a wide range of academic backgrounds, and some may not have studied chemistry at all prior to taking the course.

GTAs also acknowledged that students found them more approachable than lecture professors, often feeling more comfortable asking questions and seeking help. Amy observed, "*Students are more willing to come to me with questions... TAs are a lot more approachable.*" Caleb added, "*The students are more friendly with us. That probably has to do with just the smaller class size, honestly, because we can individually talk to each one.*"

Despite these positives, GTAs also described several frustrations and limitations. Multiple TAs emphasized a disconnect between lab instruction and the lecture content. Amy commented, "*Sometimes I didn't really see the connection between lab and lecture.*" Similarly, Daisy noted, "*There's a separation between labs and lectures.*"

Facilities and training quality were also criticized. Amy stated, "*The quality of laboratory equipment affects how students and TAs feel about lab.*" Daisy explained, "*The lab trainings, people just read procedures. It's better to discuss course materials and learning outcomes.*"

4.4.2 GTAs' Perceptions of the Diagnostic Test & Mini-Lecture

The diagnostic test and mini-lecture were consistently acknowledged by four interviewees as effective tools for self-assessment and concept reinforcement. Most participants noted that these tools offered an opportunity to refresh material that was unfamiliar or long forgotten. For example, Amy admitted, "*When I first saw [diagnostic test], I thought it was kind of difficult... it showed me what I needed to brush up on.*" Similarly, Caleb described the test as a valuable checkpoint: "*There are some topics in Gen Chem that we don't use in* *our research... I think the diagnostic test was cool.*" Caleb also commented that: "*I think it can be easy for someone to trick themselves, I'm in grad school, I know all the gen chem. So, I think the diagnostic test was cool, at least for us to see where our weaknesses are and in that way we can prepare for the coming up material for our students and just get an idea of where we need to refresh.*"

However, Daisy noted that the diagnostic test felt somewhat lengthy, stating, "*I think the number of questions might have been a bit, maybe you can cut it down for like two thirds of that. But I think it's good. It helps to get a background, get an idea about the background.*"

GTAs generally viewed the mini-lecture as a useful and time-efficient method for correcting misconceptions and improving content confidence. Amy appreciated the lecture as "*a little refresher on the topic and subject.*"

Bob found the format particularly engaging, stating, "*You made all of us look like we didn't know (about the content) ... it made me wake up and realize you need to listen*." Bob particularly appreciated the refutational nature of the mini-lecture, stating, *"...because if you're just to lecture at them, they're not going to listen. Usually if you ask them a question, and then like, 'this is for sure the answer,' and then you tell them, that's not the answer... that made me kind of wake up and realize, Oh, you do need to listen to this.*"

Caleb emphasized the mini-lecture's role in promoting readiness to teach and reducing last-minute content review. "*It was nice that it kind of prepared us for what we were going to talk to,*" Caleb said, adding that mini-lectures could potentially save time in the long run. Daisy echoed this idea, saying that even experienced TAs benefit: "*It gives more information and helps people who might know it already but need help to refresh their knowledge*."

4.4.3 Future Support for TAs

GTAs shared a variety of actionable suggestions for how departmental training and resources could better support their instructional roles. A central theme in their recommendations was the desire for structured, concise, and reusable instructional materials. Amy proposed, "*If we had a little condensed manual summarizing topics... that would be helpful.*" Bob elaborated on this idea, suggesting "*a pamphlet with rules, sig figs, equations, like a quick go-to.*" Caleb describe an example of a slide-based format: "*Maybe a PowerPoint specifically for TAs with fundamental concepts for labs.*" These proposed materials would provide immediate, on-hand support as TAs prepared for recitations and labs each week. In terms of format, TAs advocated for resources that combine concise overviews with brief quizzes or sample questions to reinforce their understanding. Amy suggested that including both bullet points and short quizzes could maximize usefulness: "*Maybe both? A mini manual and a few questions just to test your knowledge.*"

GTAs also expressed strong opinions about the scheduling and delivery of the support. Bob recommended holding monthly mini-lectures that summarize concepts relevant to all labs that month. Caleb favored a more frequent approach, stating, "*Having a mini-lecture every week wouldn't be too much. It saves more time in the long run.*" Daisy offered a hybrid suggestion: "*Maybe 5–10 minutes* *before the mini lecture, do a quiz to refresh their knowledge.*" This, they argued, would ensure that the mini-lecture content was more targeted and engaging.

One of the most emphasized forms of support was clearer alignment between lab content and lecture material. TAs noted that they often felt unprepared to make these connections on their own. Amy suggested that "*highlighting points that the TAs need to talk about*" would guide them more effectively. Daisy called for deeper integration of content guidance into existing TA meetings: "*That time slot can be better optimized... then the TA will get a better understanding of what they're supposed to do.*" Caleb proposed creating materials that "*clearly outline what students are expected to learn from each lab*," which could serve as a teaching guide.

4.5 Discussions

As shown in ***Table 4-1, 4-17 and 4-20***, the Spring 2023 cohort achieved a higher average score on the Chemical Equilibrium Diagnostic Test (CEDT) compared to the Fall 2023 cohort. Although this difference was not statistically significant, one possible explanation is that the Spring 2023 GTAs had already completed one semester of teaching CHEM 1, which may have provided them with greater familiarity with the course content. However, despite this prior experience, GTAs in the Spring cohort still demonstrated a variety of misconceptions on both the pre- and post-assessments. This finding suggests that the use of a diagnostic test and a targeted mini-lecture remained necessary and valuable for addressing persistent conceptual gaps.

Observations of laboratory sessions revealed variability in how GTAs introduced the background concepts related to chemical equilibrium. Some GTAs spent little to no time discussing the underlying chemistry while others spent more than ten minutes to explain equilibrium principles. This inconsistency may result in unequal learning experiences for students enrolled in different lab sections, even though they are taking the same course. Some students may receive sufficient conceptual grounding, while others may leave the lab without a clear understanding of the key ideas.

Additionally, some GTAs from both semesters used analogies to help students grasp the abstract concept of dynamic equilibrium. Although well intentioned, many of these analogies lacked clarity or accuracy, and in some cases, may have contributed to further confusion. For example, analogies involving water flow or physical balancing were sometimes introduced without sufficient explanation or connection to the actual behavior of chemical equilibrium.

While both semesters showed improvement in post-assessment scores, the mixed ANOVA analysis did not indicate a statistically significant effect of the mini-lecture intervention. Nonetheless, item-level analyses revealed that the mini-lecture seemed to support improvements specifically in predicting equilibrium shifts. In contrast, little to no improvement was observed in questions related to concentration changes or understanding of the equilibrium constant. One possible explanation is that the mini-lecture focused heavily on Le Châtelier's Principle and did not include a detailed discussion or example involving equilibrium constant calculations. To address this gap, future iterations of the mini-lecture could incorporate explanations and examples involving equilibrium constants to further prove the effectiveness of the mini-lecture.

Based on feedback from interviews and observations, it appears necessary to provide GTAs with a standard set of instructional materials to support more consistent and accurate teaching across lab sections. This approach would ensure that all students are introduced to core equilibrium concepts in a uniform way, regardless of their assigned GTA. Standardized materials would also help prevent the spread of misconceptions, particularly when GTAs rely on their own analogies or explanations that may be incomplete or incorrect.

Chapter 5 Conclusions, Limitations, Implications and Recommendations

5.1 Conclusions

<u>**Research Question 1:** What misconceptions about chemical equilibrium do first-year teaching assistants (TAs) in CHEM 1 hold before teaching the topic in the "Reversible Reactions" laboratory session?</u>

The pre-assessment revealed that GTAs from both the Spring 2023 and Fall 2023 cohorts exhibited a variety of misconceptions, many of which were similar across the two groups.

The first section of the CEDT included three questions designed to assess GTAs' prerequisite knowledge related to chemical equilibrium – specifically, their understanding of reaction rate. A common misconception observed in both cohorts was the conflation of thermodynamic and kinetic concepts.

When defining reaction rate, one GTA (TA10) from the Spring 2023 stated that "*…it can determine if the reaction will be forward or reverse,*" while one GTA (TA8*) from the Fall 2023 cohort stated, "*The rate of the reaction is the concentration of products over the concentration of reactants.*"

Although most GTAs in both groups were able to provide a general definition of reaction rate, 30% of Spring 2023 GTAs and 55% of Fall 2023 GTAs were unable to use stoichiometry to calculate the rate of formation or consumption of other substances in a chemical reaction. This phenomenon was also noted in Jusniar's study.[110] Furthermore, with the exception of TA9* from Fall 2023, GTAs from both cohorts showed limited understanding of the mathematical expression for reaction rate. Many did not recognize that the rate should be expressed as the change in concentration over time, where concentration is measured in moles per liter (mol/L) rather than simply in moles. This misunderstanding persisted in responses to questions in the second section of the CEDT.

When asked why increasing the temperature results in a faster reaction rate, only about 50% of GTAs from each cohort incorporated appropriate concepts such as "kinetic energy" or "collision theory." Two GTAs from Spring 2023 and five from Fall 2023 incorrectly explained that the rate increases because the reaction is endothermic. TA5 from Spring 2023 referenced the Gibbs Free Energy equation, and TA11* from Fall 2023 attempted to use entropy to justify the increase. Both responses further indicate the confusion between thermodynamic and kinetic principles.

Moreover, several GTAs also wrote incorrect equations that did not align with the IUPAC definition of reaction rate, the equilibrium constant expression, or the rate law. Examples include: "$rate = K\frac{[Products]^x}{[Reactants]^y}$", "$K_c = \frac{d[Products]}{d[Reactants]}$"", and "$Rate = [Product]/[Reactant] \cdot Time$".

The second section of the CEDT assessed GTAs' understanding of how equilibrium shifts in response to changes in temperature, pressure, and the addition or removal of reactants or products. It also required them to determine how these changes affect the rate of reaction, concentrations of certain reactants or products, and the equilibrium constant. No question in this section was answered correctly by all participants, suggesting that both cohorts had only a partial understanding of how equilibrium systems respond to changes.

Four key misconceptions, observed in both the Spring and Fall cohorts and supported by previous research, include:

1) Incorrectly predicting the direction of equilibrium shift for an exothermic reaction when temperature is lowered;
2) Misapplying Le Châtelier's Principle to predict changes in reaction rate (also observed in Banerjee's study[5]);
3) Confusing the concepts of amount (moles) and concentration (also reported by Wheeler and Kass[61]);
4) Believing that removing a reactant changes the value of the equilibrium constant (also observed by Wheeler and Kass[61]);

In addition to these four misconceptions, 20% of GTAs from the Spring 2023 cohort believed that halving the volume does not cause an equilibrium shift. Moreover, 36% of GTAs from the Fall 2023 cohort believed that removing one reactant leads to a passive decrease in the amount of another reactant.

Notably, no GTA in either semester correctly answered Question 4. The question asked: "*1 mole $COCl_2$, and 0.01 mole Cl_2 is added to the system at constant volume and temperature. When the system returns to another equilibrium, how does the mass of CO change?*" No respondent selected the correct "data insufficient" option. This pattern suggested a misconception that GTAs overused Le Châtelier's Principle to predict quantitative outcomes, such as changes in mass, without applying the equilibrium constant through a mathematical expression.

Research Question 2: What misconceptions do TAs demonstrate while teaching chemical equilibrium during the "Reversible Reactions" laboratory session?

Through classroom observations, we found that some misconceptions were unintentionally conveyed by GTAs to their students.

In Spring 2023, three out of the seven observed GTAs did not present the concept of chemical equilibrium. They spent approximately three minutes covering only the general procedure of the laboratory. The remaining four GTAs (TA3, TA6, TA8, and TA9) introduced the concepts of reversible reactions and Le Châtelier's Principle to varying extents. Among them, TA6 and TA8 defined both "reversible reactions" and "chemical equilibrium," whereas TA3 did not define chemical equilibrium, and TA9 did not define reversible reactions.

In the presentation, TA6 described equilibrium as a state where the reaction has occurred and "nothing is leaving the system." TA6 also stated that the double arrow means the forward and reverse reactions occur at the same rate constant. In another statement, TA6 said, "This is a reversible reaction, which means that the rate of the forward reaction is equal to the rate of the reverse reaction." These comments reflect a significant misconception. TA6 appeared to treat reversible reactions and chemical equilibrium as the same. In reality, the forward and reverse reaction rates are equal only when equilibrium is established. A reversible reaction alone does not guarantee equal rates. Additionally, the double arrow symbol indicates that the reaction is reversible but does not imply that equilibrium has been reached. A similar misunderstanding was reported in Banerjee's study.[5]

TA6 also incorrectly stated that decreasing pressure increases volume and then causes the equilibrium to shift toward the side with less moles. This misconception was consistent with TA6's response on the CEDT, where TA6 indicated that increasing pressure would cause the mass of the reactant CO to increase.

Another example of a misconception was observed in TA9's presentation. TA9 stated, "When the equation reaches equilibrium, the concentration of A and B are the same." This reflects a common misunderstanding. At equilibrium, the forward and reverse reaction rates are equal, but the concentrations of reactants and products are not necessarily the same. This misconception was also documented in Gage's study.[69]

Unlike in Spring 2023, GTAs in Fall 2023 were provided with instructional slides prepared by the general chemistry team. However, only one GTA (TA6*) used the slides during their teaching.

Overall, GTAs in Fall 2023 spent less time introducing chemical equilibrium concepts compared to those observed in Spring 2023. Most presentations lasted approximately 3 to 5 minutes and placed greater emphasis on laboratory procedures than on conceptual understanding.

Among the seven GTAs observed, only one (TA4*) did not mention chemical equilibrium concept at all. The remaining six GTAs all provided a definition of reversible reactions, but only two (TA3* and TA8*) defined chemical equilibrium during their introductions.

A notable misconception was identified in TA8*'s explanation, where equilibrium was described as a state in which all substances coexist. TA8* also defined a reversible reaction as one that "goes forward and then back," a description that may lead to the misconception of viewing reversible reactions as oscillating processes. This type of misunderstanding is similar to what was reported in the study by Bergquist and Heikkinen.[64]

Research Question 3: How do TAs' misconceptions change after attending the mini-lecture?

The analysis of pre- and post-assessment results from both Spring and Fall 2023 suggests that attending the mini-lecture was associated with conceptual gains among GTAs. Although mixed ANOVA results in both semesters indicated no statistically significant interaction between attendance and score changes, qualitative analysis of item-level responses revealed notable conceptual gains among attendees. These gains were especially apparent in the first section of the Chemical Equilibrium Diagnostic Test (CEDT), where several attendees revised their definitions of reaction rate to include "concentration change over time" and began using IUPAC-style mathematical expressions. Additionally, some attendees shifted from incorrect or vague explanations to more accurate ones that referenced collision theory and kinetic energy, both of which were emphasized during the mini-lecture.

In the second section of the CEDT, which assessed understanding of equilibrium shifts, reaction rate relationships, and the equilibrium constant, attendees in both semesters showed improvement in a greater number of questions than non-attendees. In contrast, non-attendees typically showed minimal change or repeated the same errors in their post-assessments.

The mini-lecture appeared to be effective in addressing certain misconceptions, particularly in the application of Le Châtelier's Principle and in helping GTAs distinguish between thermodynamic and kinetic reasoning. However, some misconceptions persisted despite the intervention. For instance, GTAs in both semesters continued to show limited understanding of questions related to the equilibrium constant, and many still confused the concepts of amount in moles with concentration.

Research Question 4: What are TAs' perceptions of the mini-lecture, and what additional support do they believe would enhance their teaching as GTAs?

All four interviewed GTAs expressed positive attitudes toward the mini-lecture. They found it helpful for reinforcing content knowledge, particularly through its refutational format, which challenged their preconceptions and encouraged deeper engagement. Several participants noted that the mini-lecture served as an effective refresher, allowing them to revisit foundational topics they had not used recently in their graduate studies.

When asked about additional support that could improve their teaching, GTAs commonly expressed the need for a concise and accessible resource. They suggested the creation of a manual or pamphlet containing bullet points, key equations, and essential concepts aligned with each chapter of the General Chemistry I curriculum. Some also proposed having access to pre-made PowerPoint slides that could be used directly during recitation or laboratory instruction to save preparation time and ensure consistency.

Furthermore, participants expressed a preference for more practical, content-focused training. Rather than spending time on general pedagogical theory, they recommended using weekly TA meetings to directly review the material they would be teaching in the upcoming week. This approach, they believed, would better prepare them for instruction and help ensure that students receive accurate and coherent guidance throughout the course.

5.2 Limitations

The most significant limitation of this study was the small sample size. Only 10 GTAs from Spring 2023 and 11 GTAs from Fall 2023 participated in the assessment, which limited the statistical power of the analysis. As a result, the study may be susceptible to a Type II error, where the statistical tests fail to detect a real effect that does, in fact, exist.[121]

Another limitation lies in the scope and content of the mini-lecture itself. The mini-lecture included only three interactive questions, primarily designed to review the definition of reaction rate and the conditions that affect chemical equilibrium according to Le Châtelier's Principle. Due to time constraints, the mini-lecture did not cover all key concepts related to chemical equilibrium.

Instead, it focused more narrowly on content emphasized in the CHEM 1 curriculum. As a result, GTAs may not have received sufficient reinforcement in areas such as equilibrium constant calculations or concentration-based reasoning.

In addition, the design of the Chemical Equilibrium Diagnostic Test may have introduced limitations in identifying misconceptions. To reduce the time burden on participants, a one-tier multiple-choice format was used. While this format allowed for efficient data collection, it may have led to an overestimation of misconceptions, as incorrect responses could result from guessing or even lack of understanding.

Practical considerations also played a role in shaping the study design. Because participants did not receive compensation, both the diagnostic test and the mini-lecture were intentionally kept brief to encourage participation and respect GTAs' limited availability. While this helped maintain engagement, it may have limited the depth of learning and diagnostic insight the tools could provide.

Lastly, there may be a self-selection bias among the GTAs who agreed to be interviewed. All four participants expressed a strong interest in teaching and a desire to support their students, which may not be representative of the broader GTA population. Their positive attitudes may have influenced the nature of the feedback collected. It would have been valuable to include the perspectives of GTAs who are less enthusiastic about teaching, in order to better understand their needs and how to support them more effectively. Anecdotal feedback from the broader group still suggests a general desire for reduced workload and more practical, targeted support from the department.

5.3 Implications and Recommendations

The findings of this study suggest that even GTAs with undergraduate degrees in chemistry or related science fields may still hold misconceptions about foundational topics in general chemistry. This echoes the need for timely and targeted refresher resources to better prepare GTAs before they teach content such as chemical equilibrium.

Although efforts were made to keep the mini-lecture and diagnostic test brief, GTAs still expressed a desire for shorter diagnostic test. Their feedback again suggests the importance of ready-to-use instructional resources that reduce the time and effort GTAs must spend preparing for their teaching responsibilities.

One practical recommendation is to develop a concise teaching pamphlet that outlines the core concepts for each chapter in the CHEM 1 curriculum. In addition, providing pre-made PowerPoint slides for use in both recitation and laboratory settings could help ensure consistency across sections and reduce individual preparation burdens. It is also recommended that the department require all GTAs to use these standardized materials, both to maintain instructional consistency and to prevent the introduction of personal misconceptions into the classroom.

Another possible strategy is to implement short, weekly online mini-lectures and diagnostic quizzes through platforms such as Canvas. These modules could include a few well-designed questions and brief content reviews, taking no more than 10 minutes to complete. This approach would help GTAs continuously refresh their knowledge without adding significant workload. Since many general chemistry programs at universities across the United States follow similar curricular structures, these materials could potentially be shared across institutions, benefiting a broader population of GTAs in the long term.

There is also a need for broader pedagogical discussions about how the concept of chemical equilibrium is taught. Previous research[58, 71, 72] has raised concerns about the overuse of Le Châtelier's Principle as a one-size-fits-all explanation for chemical behavior. While useful as a qualitative tool for predicting the direction of equilibrium shifts, Le Châtelier's Principle should not be treated as a substitute for more rigorous, quantitative reasoning.

It is also important for both GTAs and lecture instructors to recognize the necessary conditions under which Le Châtelier's Principle applies. In many cases, instructors do not explicitly mention assumptions such as constant temperature or constant volume when teaching this concept. These conditions are often taken for granted. However, overlooking or failing to clarify these prerequisites can lead to confusion and misconceptions, especially when students try to apply the principle to unfamiliar or more complex systems.

While designing the diagnostic test, I began to question whether the IUPAC definition of reaction rate should be re-evaluated. According to the IUPAC definition[122], reaction rate is defined as the change in concentration over time. However, many textbooks[123] do not clarify that this definition is only applicable to substances in the aqueous or gaseous phase, since solids and pure liquids do not have defined concentrations. This omission may contribute to confusion among both students and instructors. It is recommended that textbooks and instructional materials include explicit clarification about the proper application of the IUPAC definition of reaction rate, especially when teaching at the introductory level.

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Appendix

Appendix A

The UNIVERSITY of OKLAHOMA

Institutional Review Board for the Protection of Human Subjects

Approval of Initial Submission – Exempt from IRB Review – AP01

Date: June 17, 2022 **IRB#:** 14492

Principal Investigator: Diya Tang

Approval Date: 06/17/2022

Exempt Category: 2

Study Title: Help Students Succeed - Through Uncovering Teaching Assistants' Misconceptions in Chemical Equilibrium

On behalf of the Institutional Review Board (IRB), I have reviewed the above-referenced research study and determined that it meets the criteria for exemption from IRB review. To view the documents approved for this submission, open this study from the *My Studies* option, go to *Submission History*, go to *Completed Submissions* tab and then click the *Details* icon.

As principal investigator of this research study, you are responsible to:

- Conduct the research study in a manner consistent with the requirements of the IRB and federal regulations 45 CFR 46.
- Request approval from the IRB prior to implementing any/all modifications as changes could affect the exempt status determination.
- Maintain accurate and complete study records for evaluation by the HRPP Quality Improvement Program and, if applicable, inspection by regulatory agencies and/or the study sponsor.
- Notify the IRB at the completion of the project.

If you have questions about this notification or using iRIS, contact the IRB @ 405-325-8110 or irb@ou.edu.

Cordially,

Lara Mayeux, Ph.D.
Chair, Institutional Review Board

Appendix B

The UNIVERSITY of OKLAHOMA

Institutional Review Board for the Protection of Human Subjects

Approval of Initial Submission – Exempt from IRB Review – AP01

Date: April 10, 2023 **IRB#:** 15609

Principal Investigator: Diya Tang

Approval Date: 04/10/2023

Exempt Category: 1 & 2

Study Title: Help Students Succeed - Through Uncovering Teaching Assistants' Misconceptions in Chemical Equilibrium

On behalf of the Institutional Review Board (IRB), I have reviewed the above-referenced research study and determined that it meets the criteria for exemption from IRB review. To view the documents approved for this submission, open this study from the *My Studies* option, go to *Submission History*, go to *Completed Submissions* tab and then click the *Details* icon.

As principal investigator of this research study, you are responsible to:

- Conduct the research study in a manner consistent with the requirements of the IRB and federal regulations 45 CFR 46.
- Request approval from the IRB prior to implementing any/all modifications as changes could affect the exempt status determination.
- Maintain accurate and complete study records for evaluation by the HRPP Quality Improvement Program and, if applicable, inspection by regulatory agencies and/or the study sponsor.
- Notify the IRB at the completion of the project.

If you have questions about this notification or using iRIS, contact the IRB @ 405-325-8110 or irb@ou.edu.

Cordially,

Aimee Franklin, Ph.D.
Chair, Institutional Review Board

Appendix C

The Observational Protocol

TA Participant Code:			
TA's Lecturing		Students' Reaction	
Descriptive Notes	Reflective Notes	Descriptive Notes	Reflective Notes

Appendix D

Chemical Equilibrium Diagnostic Test

1. Consider a reaction where chemicals 'A' and 'B' react to form 'C', $A + B \rightarrow C$. Explain in your own words what you understand by the term "rate of reaction."

____

2. The $Mg\ (s) + 2HCl\ (aq) \rightarrow MgCl_2\ (aq) + H_2\ (g)$ reaction experiment was carried out. An increase in temperature can cause an increase in the reaction rate. The proper explanation for this is…

____

3. At a temperature of 25 °C a reaction occurs as follows:

$$Na_2S_2O_3\ (aq) + 2HCl\ (g) \rightarrow 2NaCl\ (aq) +\ H_2O\ (l) + SO_2\ (g) + S\ (s)$$

If the rate of formation of sulfur is 2 mol/min, then...

(A) the rate of reduction of sodium thiosulfate is 1 mol/ min

(B) the rate of formation of sodium chloride is 4 mol/min

(C) the rate of formation of sulfur dioxide is 1 mol/min

(D) the rate of formation of sodium chloride is 2 mol/min

Based on the information above, can you determine the rate of the reaction?

If yes, explain how:

____

If no, explain why:

____

4. Consider an equilibrium mixture of CO, Cl_2, $COCl_2$ at 200 °C and 1 atmosphere pressure present in chemical equilibrium:

$$CO\ (g) + Cl_2\ (g) \rightleftharpoons COCl_2\ (g) + heat$$

Responses for questions (1) to (5) are to be given as: A: greater than the initial amount; B: less than initial amount; C: same as the first equilibrium; D: data insufficient for conclusion

(1) The mixture is cooled to 150 °C, keeping the volume constant. When the system returns to a new equilibrium,

  (a) the mass of $COCl_2$ present will be...
  (b) the rate at which $COCl_2$ is being formed will be...
  (c) the equilibrium constant will be…

(2) The volume of the system is halved by increasing pressure at constant temperature. When the system returns to a new equilibrium,

  (a) the mass of $COCl_2$ present will be...
  (b) the concentration of $COCl_2$ present will be...
  (c) the mass of CO present will be...
  (d) the concentration of CO present will be...

(3) Some Cl_2 is removed from the system, the volume and the temperature being kept constant. When the system returns to a new equilibrium,

  (a) the mass of CO will be…
  (b) the equilibrium constant will be...

(4) 1 mole $COCl_2$, and 0.01 mole Cl_2 is added to the system at constant volume and temperature. When the system returns to another equilibrium, how does the mass of CO change? Include the rational.

(5) When temperature is increased, the rate of the forward reaction will

  (a) Increase
  (b) Decrease
  (c) Unchanged
  (d) Data insufficient for conclusion