# Chemistry Graduate Students' Knowledge for Teaching and Factors That Influence Their Development as Instructors

by

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# Abstract

Chemistry graduate teaching assistants (GTAs) play a unique but important role in undergraduate STEM education. As leaders of laboratory and discussion sections, GTAs teach fundamental experimental techniques and reinforce course content in classrooms and have more opportunities to interact with students one-on-one or in small groups. GTAs often teach sessions independently; however, they engage in minimal training in preparation. Furthermore, GTAs simultaneously balance research and academic requirements, which are often regarded as more important for graduation than teaching development. As universities implement evidence-based teaching strategies, including in laboratory settings, the expectations of GTAs become more complicated and thus GTAs require additional support for their teaching. The call to improve GTA teaching resulted in recent efforts within the chemistry education research field to investigate and describe elements of chemistry GTAs' content and teaching knowledge and their experiences in different types of classrooms. A number of chemistry GTA training programs have been developed, implemented, assessed, and disseminated, though the need to improve GTA teaching remains.

The work presented herein expands on our current understanding of GTAs' teaching knowledge and practices by considering the overlap of GTAs' knowledge, identities, and social context in which they work. This work was guided by several research questions, including (1) What is the nature of chemistry GTAs' knowledge for teaching organic chemistry mechanisms? (2) What is the nature of GTAs' teacher knowledge and teacher identity, and what factors influence their development? (3) What sociocultural aspects of GTAs' environments inform their teaching? (4) How does a GTAs' teacher learning shift as they gain experience in their social context? and (5) What do chemistry GTAs notice about their students during class sessions, and how do they interpret what they notice? Investigating these questions was guided by several theoretical frameworks, including pedagogical content knowledge, which describes teaching knowledge as a transformation of content knowledge, and the sociocultural theory of teacher learning, which considers teachers' contexts as a critical influence as teachers learn to teach. All four studies involved collecting interviews with chemistry GTAs; two studies also involved collecting observational data. Interviews and observations were qualitatively analyzed to investigate relevant research questions. A case study approach was utilized in one study to deeply investigate the experiences of a few first-year GTAs.

Findings indicate that GTAs' content knowledge varies, impacting their teaching knowledge. In the absence of substantial training, GTAs rely on their content knowledge and prior experiences to inform their teaching; this contributes to a barrier preventing GTAs from implementing evidence-based practices because many GTAs' prior experiences as students were in traditional lecture-style classrooms. Additionally, the focus of research within the culture of chemistry departments inhibits GTAs' development of teacher identity, which in turn inhibits their development of teaching knowledge. While GTAs' pedagogy does develop with experience as a GTA, this development occurs in relatively isolated environments without support for their development. Findings from this work contribute to our understanding of chemistry GTAs' teaching experiences within their unique contexts, which suggests that a single training program may be insufficient in preparing GTAs to teach with evidence-based practices in their current role and in their future academic roles. An ongoing training program, where GTAs have space to interact with other instructors to reflect on and grow from their experiences, might accelerate GTAs' teacher learning and support their implementation of evidence-based practices.

# Chapter 1

# Introduction

## 1.1 Document overview

This document contains a collection of articles that comprise the author's published and 'in preparation' bodies of work. The introductory chapter summarizes the larger body of chemistry education research related to graduate students' experiences as graduate teaching assistants (GTAs) and the efforts made to design training programs to support GTAs' development. Subsequent chapters correspond to the author's research studies investigating chemistry GTAs' teacher knowledge and factors that influence their development as instructors. Each subsequent chapter contains initial remarks highlighting the significance of each study, research findings, insights into the GTA experience, original publication and copyright information, and contributions by coauthors. Chapter 2 corresponds to a study on chemistry GTAs' knowledge for teaching organic chemistry mechanisms. Chapter 3 corresponds to a study on chemistry GTAs' general teaching knowledge (not content-specific), their teacher identities, and factors that influence GTAs' teacher knowledge and identity. Chapter 4 corresponds to a case study investigating three chemistry GTAs' development over time and with experience as an instructor. Chapter 5 corresponds to a study on GTAs' noticings in their classrooms. The concluding chapter contains closing remarks.

## 1.2 Abstract

Graduate teaching assistants (GTAs) hold a unique position, as they not only teach undergraduate laboratory and discussion classes, but also balance their own research and academic responsibilities. Further, GTA training is often short and focused on classroom logistics, leaving GTAs to rely on their prior experiences and content knowledge to inform their teaching. Chemistry education researchers have worked to both better understand how graduate students take on their GTA role and to better prepare GTAs through various training programs. This chapter includes a summary of papers that are focused on chemistry GTAs and recommendations for future research.

## 1.3 Background

### 1.3.1 The context of graduate teaching assistant roles

At doctoral research institutions, chemistry graduate students typically begin their experience with an orientation to the university. Orientation may include an overview of university policies, expectations for graduate school, a description of important milestones, and an introduction to their duties as researchers, students, and teachers.[1,2] In chemistry graduate students' first semester of graduate school, they often begin taking their graduate-level courses, join a research lab, and start their instructional role as a GTA. GTAs are typically expected to devote ten to twenty hours per week instructing undergraduate students in discussion or laboratory sessions, preparing to teach, assessing and grading student work, attending associated lectures, and hosting office hours. The remainder of their week is occupied by academic and research responsibilities. In discussion sessions, GTAs may teach new content, reinforce content taught in lecture, answer students' questions, and guide students' thinking about course content. In laboratory sessions, GTAs may review relevant content and guide students through experiments and data analysis. Because laboratory and discussion sections are typically composed of twenty to thirty undergraduate students, GTAs often have more facetime with undergraduate students than instructors who teach large-enrollment introductory lectures.[3] Additionally, at research institutions, 70% of undergraduate life and physical science laboratories are taught by GTAs.[4] Thus, GTAs are in a position to influence undergraduate students' learning and attrition in undergraduate science courses.[5]

With a national call to increase the implementation of evidence-based teaching practices in higher education, universities often turn to undergraduate laboratory courses to fulfil this requirement. The structures of chemistry laboratory courses have, in some cases, been transformed from direct, "cookbook"-style laboratory protocols to inquiry-based laboratory protocols. In cookbook labs, students follow a prescribed list of actions to complete a laboratory experiment. In inquiry-based labs, students use their knowledge to make observations, ask questions, and set the context for their laboratory experiment. While inquiry-based labs have been shown to better support student learning in laboratory courses, to be successful, the laboratory instructor must have the skills to appropriately guide students in their inquiries. At large research institutions, this responsibility falls on the GTAs who teach undergraduate chemistry laboratories.

GTAs are a particularly unique population of instructors because they hold such an important role in undergraduate education; however, they are simultaneously balancing significant academic and research responsibilities. At large institutions, research responsibilities often are expected to be prioritized over teaching responsibilities, likely because both graduate student success (i.e., completing PhD requirements) and faculty success (i.e., obtaining grant funding and completing requirements for tenure) rely on successfully completing research projects. This prioritization of research over other responsibilities contributes to the research-focused culture in chemistry and other STEM departments,[2,6] wherein teaching is sometimes viewed solely as a source of funding for graduate students.[7] While building research skills is a critical part of graduate school, more concentration on developing teaching skills may be beneficial to graduate students. Not only do GTAs impact student learning while they lead laboratory and discussion sections, one in three STEM doctoral students will become instructors after completing their PhD programs.[8] Because the teaching experiences that chemistry GTAs have in graduate school often influence their teaching as chemistry instructors in the future, it is important to support GTAs' development as instructors.[9] The chemistry education research community has placed focus on understanding GTAs' experiences, factors that influence their teaching as GTAs, and facilitating their development as instructors over time.

### 1.3.2 Factors that influence teaching

For decades, researchers have concerned themselves with the development of instructors' knowledge and skills for teaching. Many theories have been derived and utilized to understand the factors that inform teachers' actions in the classroom and how they evolve over time. Three of constructs are described in later chapters of this dissertation: pedagogical content knowledge[10] (Chapter 2), sociocultural theory of teacher learning[11] (Chapters 3 and 4), and teacher noticing[12] (Chapter 5). Generally, teachers' prior experiences in instructional settings—whether as the student or as the teacher—influence teachers' beliefs about how teaching and learning occur. These beliefs then influence teachers' knowledge about how to teach, how to assess learning, and their identities as teachers.[13] Teachers' knowledge for teaching and their identities as teachers influence their actions in the classroom.[14–18] All of these factors—beliefs, knowledge, identity, and actions—may also be influenced by engaging in professional development activities, interacting with peers and mentors in their teaching context, and reflecting on their own experiences. Thus, instructors are constantly building their knowledge and skills for teaching and their teacher identities. Teaching specific content is also tied to teachers' content knowledge.[19] In this chapter, I summarize the chemistry education research community's current findings related to chemistry GTAs' teaching and the training programs that have been developed to support GTAs in their role.

## 1.4 Methods

To collect articles for this chapter, I utilized the Education Resources Information Center (ERIC) database to search for articles related to chemistry GTAs.[20] My search criteria included the following key words: "chemistry," "graduate teaching assistant," "teaching assistant," "graduate student," "graduate student instructor," and "doctoral student." I further narrowed the articles that this search generated to peer-reviewed articles published in the year 2000 or later,[20] though I excluded the articles for which I am the first author as they are included as chapters in this document. Finally, I narrowed the resulting set of articles to those that were specifically focused on chemistry graduate students' roles as GTAs; I excluded studies and trainings focused on their development as researchers. In this chapter, I summarize the 48 articles that resulted from this search.

Research related to chemistry GTAs' teaching and learning to teach is sparse, but each finding helps us understand GTAs' experiences. In this chapter, I first describe current findings related to the factors that influence GTAs' teaching: perceptions of their duties as GTAs, prior experiences, and content knowledge. I then describe findings related to GTAs' teaching knowledge. In the following section, I summarize findings from research projects that have specifically investigated GTAs' teaching actions in their classroom and what we know so far about how graduate students' experiences in their role as GTAs influences their teaching over time. In the final section, I report on training programs that have been implemented and published over the last two decades. This chapter concludes with comments and recommendations for future research and chemistry GTA training programs.

## 1.5 Factors that influence chemistry GTAs' teaching

### 1.5.1 GTAs' perceptions of their role and duties as a GTA

Perhaps the most basic factor that influences how one takes on a role is their expectations of what the role entails. Job descriptions may be communicated explicitly or implicitly in official documents, trainings, staff meetings, and social interactions. Two studies have identified the teaching competencies that chemistry GTAs believe are required for teaching undergraduate laboratory courses and compared GTAs' perceptions to faculty[21] and laboratory coordinators.[22] Deacon et al.[21] first reviewed chemistry GTA training manuals to identify competencies for teaching laboratory courses. They formed a survey from these twenty teaching competencies and asked GTAs, faculty, and laboratory coordinators to rank the listed competencies in order of importance for GTAs who work in undergraduate science laboratories. GTA participants widely agreed that the top five teaching competencies required of them were: (a) to communicate information clearly and effectively, (b) to demonstrate concern and respect for students, (c) to use fair and consistent grading strategies, (d) to stimulate and facilitate meaningful discussion with students, and (e) to demonstrate a high level of knowledge in the discipline. Faculty's rankings aligned with (a), (b), and (c) above, however, faculty highly ranked two competencies that the GTAs did not: to adequately plan and prepare for teaching sessions, and to demonstrate a high standard of ethical and professional conduct. The authors then compared GTA and faculty's highly ranked teaching competencies to GTA training manuals and found that the teaching competencies that were most frequently mentioned in the manuals largely did not align with GTAs' and faculties' highest ranked competencies. While the results of this study provide insight into what GTAs believe their role entails, which may inform how they teach in the classroom, the authors of this study suggest that GTAs may experience confusion about their role without clearly set expectations. The authors recommend that GTA training should include more specific communication about what their role entails to better prepare GTAs for their role.

Duffy and Cooper[22] specifically investigated GTAs' perceptions of how they should teach inquiry-based chemistry labs and compared GTAs' perceptions to the lab coordinator's expectations. GTAs in this study believed they should (a) spend time listening to students' questions, (b) engage in open dialogue with students, (c) spend significant amounts of time passively or actively observing students as they work, and (d) spend little time in closed dialogue, such as lecturing. GTAs' perceptions generally aligned with the lab coordinator's expectations. There was, however, a tension between the lab coordinator's expectations that GTAs do not explain content to students and GTAs who believe they sometimes needed to directly explain content to students to supplement their understanding. This misalignment is purported to stem from GTAs' lack of confidence in students, which may be a result of how GTAs were taught as students.

Research in this area demonstrates what chemistry laboratory GTAs believe their role entails. In both studies describing chemistry laboratory GTAs' perceptions of their duties, there were both similarities and differences in what GTAs believe their role to be, and what faculty expect GTAs to do as laboratory instructors. The source of misalignment could be due to many factors, such as a lack of communication between faculty and graduate students about GTAs' role, GTAs' prior experiences, or interactions with others that influence how graduate students view their role. Additional research investigating the factors GTAs draw on to inform their perception of their role would clarify the sources of discrepancies between GTAs and faculty. Notably, the work in this area is focused only on chemistry laboratory GTAs; chemistry discussion GTAs' perceptions of their role remain to be explored. Additional studies in this area may point to additional perceptions GTAs have about their role that were not identified in training manuals[21] or by an inquiry lab coordinator.[22] Finally, as GTAs' perceptions of their role provide a basis for how they teach laboratory courses, we must then investigate the ways GTAs teach their students (current work on this topic is summarized in section 1.8 of this chapter).

### 1.5.2 Prior experiences

In the absence of substantial training, instructors often rely on their prior experiences to inform their teaching. This is especially true for graduate students, who work in relatively autonomous environments[2] and thus draw on their prior experiences as students to inform their teaching as GTAs.[2,23–27] Most GTAs' prior experiences as students involved learning in a traditional lecture-style classroom where information was directly shared by the instructor.[2,23] Because GTAs' prior experiences inform their beliefs about teaching and learning, and thus how they teach their students,[24,28] GTAs experience a tension between their beliefs and knowledge of teaching and what is expected of them, especially in cases where GTAs lead inquiry-based labs.

Although Duffy and Cooper[22] demonstrated inquiry-based lab GTAs understand what is expected of them, GTAs have reportedly struggled to promote inquiry, and have recognized that they do not have the appropriate skills to help students in inquiry labs[24] nor role models for doing so.[2,23] GTA participants in multiple studies have discussed leaning on traditional teaching methods, like directly telling students information rather than guiding them to figure it out themselves, as they assume students learn best in this way.[2,23] GTAs without experience in inquiry-based labs often lack the motivation for teaching inquiry-based sessions, as they do not see the value of inquiry-style learning and prefer more direct “cookbook” labs. GTAs without motivation for teaching inquiry put forth relatively little effort in their GTA role, as compared to GTAs who did see the value of inquiry-based teaching and thus put forth more effort.[24]

These papers demonstrate that GTAs utilize their prior experiences as students to inform their teaching, which sometimes amplifies the struggles faced by GTAs teaching inquiry-based labs. Findings suggest that GTAs’ prior experiences were primarily in traditional-style courses, which impacts GTAs’ teaching. The authors of these papers express that GTAs’ beliefs about teaching and learning are rooted in these traditional methods; they believe students learn best when the instructor clearly communicates information. This impacts GTAs’ motivation for teaching inquiry-based labs, and thus the effort they put forth in fulfilling their role. Without sufficient training programs that support GTAs in confronting their traditional beliefs, chemistry departments may be unknowingly perpetuating traditional teaching styles. To better understand how GTAs’ prior experiences impact their teaching in the classroom, future work may focus on describing how GTAs navigate balancing prior experiences as students, limited experience as instructors (if any), their beliefs about teaching and learning, and expectations of their role as GTAs.

### 1.5.3 Content knowledge

One requisite for teaching chemistry is having the appropriate chemical knowledge. Decades ago, Bodner[29] conducted a project with the goal of demonstrating the conceptual chemical knowledge held by incoming graduate students. His conclusions demonstrated in part that chemistry graduate students entered graduate school with some alternative conceptions of chemical content that were resistant to change with instruction. He also demonstrated that while graduate students have chemical knowledge, they may not fully understand the concepts they have knowledge about. Following this work, Bodner and others have led multiple research projects focused on chemistry graduate students’ content knowledge. In these studies, content knowledge is not framed as content knowledge for teaching, but it is still useful to understand as it influences GTAs’ teaching. In some of these studies, graduate students represent a participant group that has (or is assumed to have) more sophisticated content knowledge than undergraduates, but less sophisticated than faculty members. Although some studies demonstrate that GTAs have more sophisticated knowledge than undergraduates,[30–33] they still hold alternative conceptions or incomplete knowledge in some fundamental chemistry topics.[34–38] Much of the research demonstrating graduate students' strengths and weaknesses in chemistry content knowledge has been situated in the field of organic chemistry. This work is summarized in the section below.

### 1.5.3.1 Content knowledge: Representational competence

Chemists often rely on symbolic representations (e.g., Lewis structures, reaction mechanisms, reaction coordinate diagrams, and NMR spectra) that describe processes that happen at the submicroscopic level (e.g., bond breaking, bond forming, intramolecular forces, and intermolecular forces) but are seen at the macroscopic level as observable or measurable events (e.g., solid compound dissolving into solvent, solid compound precipitating out of solvent, or one reaction producing a greater yield than another reaction). Thus, understanding and using chemical representations is a key component of chemistry content knowledge development. Strickland et al.[34] demonstrated graduate students' mental models of acids, bases, nucleophiles, electrophiles, and functional groups, and how they use these models to propose and describe reactions. This study revealed that graduate students focused on surface-level features of representations, indicating that their representational competence is limited. Graduate student participants in this study focused on what changed in a reaction, rather than how the change happened. Instead of interpreting the chemical properties of functional groups and predicting how they would react in certain conditions, participants used functional groups as a book-keeping tool for predicting changes in reactions. They demonstrated difficulty in describing functional groups but were more successful in describing nucleophiles and electrophiles. The sophistication of graduate students' representational competence improved with experience (senior graduate students as compared to first-year graduate students). Similarly, Bhattacharyya and Bodner[35] demonstrated that when proposing common reaction mechanisms, graduate students can successfully complete the task, but do not fully understand the meaning behind the curved arrows in a transformation. Most of their graduate student participants focused on individual entities (starting material, intermediates, products), rather than the transformations that occur within the reaction. These findings echo research on undergraduate students' knowledge of organic chemistry reactions,[39] as undergraduates struggle with interpreting many of the representations used in organic chemistry.

The authors of these papers make recommendations for improving organic chemistry instruction at the undergraduate level, since this is where graduate students initially learn these concepts. Their recommendations involve methods to build students' representational competence—a skill required to develop expertise in chemical reasoning.

#### 1.5.3.2 Content knowledge: Reasoning

Resulting from limited representational competence, graduate students view mechanisms as puzzles, which they complete by recalling pieces of knowledge and mechanisms they have worked with in the past. This product-oriented approach of puzzling contrasts the process-oriented approach of reasoning, or how they invoke their knowledge to make predictions about processes. Bhattacharyya[36] investigated chemistry graduate students' conceptions of organic acids and found that graduate students were successful in identifying strong and weak acids, but often had trouble articulating the scientific reasoning behind their choices. While graduate student participants considered multiple factors that influence acidity (bond polarization, resonance, and electronic effects), they primarily described it as a result of bond polarization. Further, they considered factors in a linear fashion without interplay between factors. Many graduate students' conceptions were consistent with what they learned in the undergraduate organic chemistry classroom and have not developed beyond that.

Kraft et al.[34] showed that when graduate students were presented with a partially completed mechanism, they often worked through the task with a case-based approach. In a case-based approach, graduate students recalled previous similar cases (or mechanisms) stored in their memory, and used this to explain, propose, or justify their solution to the task. Especially as mechanisms become more complex, this method of reasoning is not reliable because it focuses on superficial features of the reaction. In some cases, but less frequently, graduate students used rule-based reasoning, in which they invoked a single rule or piece of knowledge to complete the mechanism. This approach was also highly ineffective because graduate students did not consider multiple variables within the mechanism. Model-based reasoning was used the least often but was the most effective. When using this approach, graduate students construct an internal model of the mechanism, which considered the dynamic nature of the mechanism at hand.

These studies suggest that graduate students tend to rely on limited, categorized knowledge to reason about chemical properties and knowledge. This approach is not dissimilar to how undergraduates tackle organic chemistry,[40,41] which is unsettling as GTAs teach this content to undergraduate students. Researchers offer suggestions for developing representational competence and model-based reasoning skills in graduate students. Bhattacharyya and Bodner[37] aimed to study the development of organic chemistry graduate students and focused in part on their representational competence and reasoning skills. Unique from other studies on graduate students' content knowledge, they utilized a community of practice perspective[13,42] to understand how graduate students develop into practicing organic chemists within their community of organic chemists in graduate school. Bhattacharyya and Bodner[37] identified three interrelated factors that contribute to graduate students' development. The first factor is that graduate students must perceive the material they learn in courses and in other interactions with professors to be important to organic chemistry research. Otherwise, graduate students will focus their study on what they thought would help them do well on tests, like undergraduates. The second factor describes how to accomplish the first factor: graduate students must work on authentic activities that provide opportunities for them to construct their knowledge. In this way, they can apply the knowledge they learn in class to a scenario that resembles the work of practicing organic chemists. The authenticity of such activities promotes graduate students' development of both representational competence and reasoning, as both are required skills to complete this kind of work. The third factor supports graduate students' engagement in these activities: graduate students need support from more knowledgeable others—professors, research mentors, and experienced graduate students—to develop these skills. The authors noticed graduate students more closely represented practicing organic chemists in their third year, however, development beginning in graduate students' first year of graduate school. Bhattacharyya and Bodner[37] provide recommendations for graduate school programs that support organic chemistry graduate students' development into practitioners, rather than expert students.

### 1.5.3.3 Graduate students' content knowledge compared to undergraduate students' and faculty's

Although many of the studies summarized above demonstrate limitations in graduate students' chemistry content knowledge, other studies have compared graduate students' knowledge to undergraduate and faculty knowledge, especially in more recent years.[30–33] These studies reveal, in general, that graduate students' knowledge is more similar to faculty than to undergraduate knowledge, which indicates a possible progression of sophistication. Coll and Treagust[33] compared graduate students' knowledge of covalent bonding to that of undergraduate students and found graduate students have a slightly more sophisticated understanding of covalent bonding than undergraduate students. Galloway et al.[31] asked faculty, doctoral chemistry students, master's chemistry students, and undergraduate students enrolled in Organic Chemistry II to identify similarities across reactions shown on cards and to sort the cards based on those similarities. In general, doctoral students and faculty organized their cards in ways that were more similar to each other than to master's and undergraduate students. Doctoral students and faculty focused on the type of mechanism (rather than the type of reaction) and did not focus on structural similarities, which master's and undergraduate students did do. These findings suggest that doctoral students have more sophisticated knowledge—including representational competence—than the undergraduate students they may teach.

Bain and Towns[32] compared introductory-level undergraduates, senior undergraduates, and graduate students' understanding of the thermodynamic driving forces of chemical reactions and dissolution. This study revealed similar results; graduate students have more sophisticated knowledge and can communicate important concepts more effectively than both groups of undergraduate students. All groups of participants used heuristic-based reasoning, but graduate students typically also provided an accurate explanation of why the heuristic works when asked to do so. In a study that compared undergraduate and graduate students' assumptions when interpreting $^1$H NMR spectra, Connor et al.[30] revealed that graduate students relied almost exclusively on more sophisticated assumptions. For example, undergraduates often hold to the N+1 rule to predict peak splitting too closely, while graduate students can appropriately identify exceptions from the N+1 rule. Although studies summarized earlier in this chapter focus on limitations in graduate students' chemical knowledge, Connor et al.,[30] Galloway et al.,[31] and Bain and Towns[32] all demonstrate that graduate students' knowledge is, in some ways, more developed than undergraduate students. This may be because graduate students have more experience with the concepts at hand, and while they rely on certain patterns or heuristics, they are more familiar with exceptions to those shortcuts.

Studies focused on graduate student chemistry content knowledge demonstrate that graduate students have limited representational competence, which impacts their reasoning skills.

However, graduate students do demonstrate more sophisticated content knowledge when compared to undergraduate and master's students. The studies comparing undergraduate, graduate, and faculty content knowledge reveal specific ways knowledge develops over time, including during graduate school. Most of these studies are focused on organic chemistry content, but graduate students teach a variety of courses that require content knowledge in other areas, like visualization techniques in chemistry lab or gas laws in general chemistry. Thus, much of graduate students' content knowledge remains unexplored. While the studies summarized in this section are not framed with the goal of understanding GTAs' content knowledge for teaching, content knowledge is a prerequisite to teaching, and understanding GTAs' content knowledge helps us understand their teaching knowledge. Researchers have begun to explore chemistry GTAs' teaching knowledge, and current publications on this topic are summarized in the following section.

## 1.6 Chemistry GTAs' teaching knowledge

Because graduate students often teach discussion and laboratory sessions, where they have more facetime with undergraduate students than faculty who teach large enrollment lectures, their knowledge for teaching is of interest to the chemistry education community. Several studies have focused on graduate students' teaching knowledge, and in some cases relate this specifically to their content knowledge with the theory of pedagogical content knowledge (PCK). Since its conception by Shulman in 1986, PCK has gained traction in education research communities across disciplines.[19,43] PCK refers to the specialized knowledge that teachers possess which allows them to transform content in a way that enhances student learning of the particular content. In the past few decades, many conceptions of PCK have been published, with some of them being discipline-specific.[10,44–47] The consensus model of PCK, resulting from a recent PCK summit,[47] acknowledges and details several realms of PCK: (1) collective PCK, which refers to PCK constructed by many researchers and teachers, (2) personal PCK, which refers to individual teacher's own PCK, and (3) enacted PCK, which refers to how teacher plan and enact their teaching. While the frameworks for PCK vary slightly, there is general consensus that PCK includes knowledge of students' prior knowledge, knowledge of what makes the content difficult to learn, and knowledge of teaching strategies for particular content. Although PCK was originally developed to understand the knowledge held by K-12 educators, it has been adapted to understand the knowledge of post-secondary instructors, which provides unique insights into this population. PCK is described in more detail in Chapter 2.

Bond-Robinson[48] focused on identifying PCK in chemistry laboratories. They designed and validated two survey instruments—one to be completed by GTAs to report their PCK, and the other to be completed by undergraduate students to assess their laboratory GTA. Through this work they coined the term *PChK* to describe PCK within the *chemistry* discipline. They identified four levels of PChK for the chemistry laboratory, with each level requiring more content and/or teaching knowledge, however, the content knowledge required for each level is not specified. The author described the most sophisticated level of PChK to include teaching chemical concepts with dynamic content knowledge so the GTA can probe and guide students' reasoning. This level of PCK also involves confidence in GTAs' own content knowledge, so they can appropriately direct the learning environment. For example, a GTA who can use questioning strategies to guide students' thinking and probe for understanding of lab-related concepts has PChK at this level. The most basic level of PChK includes managing the laboratory environment and mentoring students but does not require chemical knowledge. For example, a GTA who demonstrates respect for their students and helpfulness in the laboratory holds PChK at this level. While all identified levels of PChK in the chemistry laboratory are important for GTAs to bring to lab, the two most basic levels were most commonly observed in GTA and undergraduate student responses to the surveys. The most sophisticated level was observed the least often, which Bond-Robinson[48] proposes is the reason why GTAs' teaching is "mediocre"—aligning more with a manager than an instructor. The author of this study utilized these four levels of chemistry lab PChK to inform a training programs focused on developing lab GTAs' PChK at higher levels,[49,50] which is summarized later in this chapter. While Bond-Robinson's[48] description of PChK levels in the chemistry laboratory is helpful in detailing the general teaching knowledge that lab GTAs may possess, they do not detail specific lab-related content knowledge (e.g., how to properly dispose of certain chemicals), suggesting that this work may not be theoretically well grounded in PCK theory.

Hale et al.,[25] Lutter et al.,[26] and Connor and Shultz[27] conducted studies to describe GTAs' PCK of specific organic chemistry concepts. In each study, a questionnaire was sent to graduate students to capture their content knowledge and PCK for thin-layer chromatography,[25] solution chemistry,[26] or $^1$H NMR spectroscopy.[27] Each study demonstrated that GTAs generally have higher levels of content knowledge of these topics than they do PCK. Higher levels of content knowledge were correlated with higher levels of PCK. Higher levels of PCK for teaching thin-layer chromatography[25] and solution chemistry concepts[26] was observed from GTAs that had more general teaching experience, while higher levels of PCK for teaching $^1$H NMR was only observed from GTAs who had experience teaching that specific topic.[27] This finding supports that PCK is topic-specific in nature, especially as topics become more specialized and complex. Additionally, GTAs demonstrated varying PCK for different questions related to $^1$H NMR, which suggests that PCK may develop at a problem-specific level.[27]

Across these studies, GTA participants noted that they utilized heuristics while they teach, such as "like dissolves like" for solution chemistry[26] or the N+1 rule for $^1$H NMR.[27] GTA participants with higher levels of PCK could explain limitations with heuristics, while GTAs with lower levels of PCK could not. Lutter et al.[26] suggest that the use and ability to provide chemical explanations for why heuristics fail in some cases may be used as a marker for identifying higher levels of PCK. In all three of these studies, findings suggest that GTAs' PCK develops with experience, and without targeted training programs. Participants that participated in follow-up interviews reported drawing on their experiences as students and experiences as instructors (if they had any) to inform their questionnaire responses, echoing work by Kurdziel et al.[23] and Luft et al.[2]

Knowing that learners struggle with representations used in chemistry, Baldwin and Orgill[51] explored how GTAs use representations to explain chemical concepts. The authors were particularly interested in (1) characterizing GTAs' perceptions of the challenges students face when learning about acid-base titrations in chemistry lab, (2) determining how GTAs use representations when teaching this concept, and (3) determining if and how GTAs' use of representations aligned with their perceived student struggles with acid-base titrations. While Baldwin and Orgill[51] did not use the PCK framework to guide their study, their findings align with two components of PCK: knowledge of what makes a topic difficult and knowledge of representations, and thus contribute to the field's understanding of GTAs' teaching knowledge of this topic. GTA participants perceived students to struggle with understanding underlying chemical concepts, physically doing the experiment, and carrying out required mathematical calculations associated with acid-base titrations. GTAs used representations to help students understand interactions between chemical species, how to physically carry out the experiment, analyze their data, and complete associated mathematical calculations. While the perceived student challenges and use of representations aligned for the GTA participants overall, the authors found that individual GTAs' perceptions of challenges and use of representations were not always aligned. For example, many GTAs (91%) expressed that their students struggle with understanding the underlying concepts of titration, but only 55% of GTAs mentioned using representations to address this challenge. Baldwin and Orgill[51] make recommendations for GTA training to add focus to the purpose and uses of representations in the chemistry laboratory.

Another common responsibility of GTAs is to grade student work (e.g., lab reports, exams, etc.). Herridge and Talanquer[52] sought to understand how chemistry GTAs approach evaluating and grading students' work, and to compare this to faculty approaches. The authors asked participants to evaluate student responses to a typical short-answer general chemistry exam question. They found a wide variety in how all participants completed this task. Regardless of group assignment (GTA or faculty), all participants made various explicit and implicit decisions when evaluating and grading the student responses. For example, some participants created an answer that they would expect of students and compared provided student responses to their constructed response. Other participants created an explicit rubric. Some participants only gave credit when the students' responses were exactly and explicitly correct, while others inferred students' understanding based on somewhat incomplete responses. Participants in this demonstrated high variability in their grading; the authors recommend that universities implement professional development programs focused on reducing this variability. Part of this training would include instructors reflecting on variability in grading and the implicit decisions they may not realize they make as they grade. The authors also note that there is a lack of attention to assessment, grading, evaluation, and related beliefs and practices in the chemistry education research community.

In sum, findings from studies on GTAs' teaching knowledge suggest that their PCK is limited, and that there is room for growth. Bond-Robinson's description of PChK in the chemistry laboratory[48] is informative in supporting GTAs' development of this knowledge, but without specific ties to content knowledge, more work on PCK in the chemistry laboratory is needed. The characterization of GTAs' PCK of thin-layer chromatography, solution chemistry, and $^1$H NMR spectroscopy provide frameworks for training to facilitate GTAs' development of their PCK of these topics, which are commonly taught in introductory organic chemistry laboratory courses.[25–27] GTAs' approaches to assess student learning is varied, and with only one paper on this topic, more work is needed to understand this aspect of GTAs' roles. Similar to the body of work on content knowledge, GTAs' teacher knowledge for many of the concepts taught in introductory chemistry courses remains largely unexplored. Finally, studies on teacher knowledge provide insight into how GTAs teach their sessions but may not directly translate to actions in the classroom.[53] Researchers have begun describing GTAs' teaching through observational data (summarized in section 1.8 below).

## 1.7 How GTAs teach in their classroom

While understanding GTAs' perceptions of their role, prior experiences, content knowledge, and teaching knowledge begins to paint a picture of how GTAs might teach their classes, these studies do not tell us exactly how GTAs actually teach their sessions, as self-reported teaching strategies and teaching knowledge do not necessarily translate to practice.[53] Three studies characterize the teaching of GTAs through observational data thus far, and all focus on GTAs teaching laboratory classes.[22,54,55] Velasco et al.[54] developed and validated an observation protocol to characterize general chemistry lab GTAs' instructional styles. They identified four instructional styles: (1) the waiters, who waited for students to call on them, (2) the busy bees, who were constantly being called on by students for help, (3) the observers, who spent most of their time observing students, and (4) the guides on the side, who initiated conversations with students, probed students' thinking, and praised student work. The authors found that, in this traditional instructional context, students' behaviors and student-GTA interactions were not dependent on the GTAs' teaching style, but rather were influenced by the laboratory activity. This may be due to the atmosphere that traditional laboratory courses create; students' main goal is to complete the experimental protocol provided to them.

In another study, observations of GTAs who taught inquiry-based laboratory classes indicated that they gave few lectures and spent most of class time engaged in conversations with students and making observations.[22] This aligned with GTAs' perceptions of their role and the lab coordinator's expectations for inquiry-based lab GTAs.[22] In a study focused on classroom discourse, researchers found that GTAs teaching inquiry-based labs constructed classroom discourse consistent with a constructivist learning perspective.[55] The GTAs spent most of their time eliciting student thinking and building upon it, as opposed to GTAs who taught traditional labs who spent more time telling students information.[55] These studies help to begin picturing GTAs' teaching and demonstrate that the type of class GTAs teach (inquiry-based vs traditional) does influence the actions GTAs take in the classroom. However, with only three studies involving observations of GTAs' teaching sessions, additional studies that investigate GTAs' teaching practices can help inform our theoretical understanding of GTAs' experiences as well as training to support GTAs' development. As a field, we know much more about GTAs' content and teaching knowledge than we do about their teaching practices.

### 1.8 GTAs' evolution over time

As instructors gain teaching experience, their teaching evolves, and researchers have investigated how GTAs develop with experience in this role. Most of the research in this area is focused on GTAs' teaching development in inquiry lab settings. As mentioned earlier, studies have reported that GTAs experience a tension between how they believe teaching and learning occurs (through traditional methods) and how they are asked to teach inquiry-based labs. In interviews after teaching a semester of inquiry-based labs, GTAs expressed that teaching in this way prompted them to confront their beliefs about teaching and learning and to ponder the nature of knowledge and learning.[56] Additionally, GTAs reflected on their own thinking and teaching to evaluate their own performance and adjust their teaching—this type of reflection helps facilitate teacher learning.[11,13] How this evolution impacts GTAs' teaching in the classroom, if at all, remains unclear. However, findings such as these serve to inform GTA training to help facilitate the development of inquiry lab GTAs' beliefs about teaching and learning.

Serving as an inquiry-based lab instructor also influenced GTAs' teacher identities, or how they view themselves as an instructor. Inquiry-lab GTAs' teacher identities shifted from managers of time and safety and providers of knowledge to mentors and facilitators of learning. GTAs' teacher identities as mentors or facilitators continued to increase with more experience in inquiry-based labs.[28,56] These findings are encouraging as GTAs' teacher identities can influence the ways they lead their sessions and the effort they put forth to prepare for teaching.[24] Namely, GTAs who identify more closely as laboratory managers will focus on managing laboratory, while GTAs who identify more closely as facilitators of learning will focus on facilitating student learning.

Studies on GTAs' PCK have found that teaching experience is positively correlated with their levels of PCK.[25–27] In other words, GTAs with more experience express more sophisticated PCK. This suggests that their experiences teaching content, answering students' questions, and guiding student thinking about specific content builds their knowledge base for teaching that content. In some studies, general teaching experience was correlated with higher levels of PCK.[25,26] However, in one study on GTAs' PCK of $^{1}$H NMR spectroscopy, only experience teaching that particular content was correlated with higher levels of PCK.[27]

These few studies begin to demonstrate how GTAs' teaching beliefs, identities, and knowledge evolve as GTAs participate in their roles. Findings provide both a more cohesive picture of how GTAs engage in their roles and a description of how their engagement is informed by their experiences over time. Further research connecting the development of GTAs' beliefs, identities, and knowledge to their actions in the classroom would provide insight into GTAs' teacher learning. Interestingly, GTAs demonstrate teacher development in their relatively isolated environments with limited training.[2,23] Carefully constructed GTA training and support programs, grounded in theoretical bases, may help facilitate GTAs' development as instructors and therefore impact both their teaching as a GTA and their teaching in the future as lead instructors.[8,9] The chemistry GTA training programs that are currently described in the literature are summarized in the following sections.

## 1.9 Research on chemistry GTA training programs

Chemistry education researchers have developed, implemented, and evaluated training programs to better prepare and support chemistry GTAs as they are often placed in teaching roles for which they have minimal training and experience. Published training programs range from one-day workshops to programs that span over GTAs' first year of graduate school. Several of these published training programs were designed to support chemistry GTAs in general,[57–64] while others were designed to specifically support lab GTAs, often for inquiry-based teaching.[49,50,65–71] A few trainings were designed to prepare graduate students for potential future roles as teaching faculty.[72–74] The training programs summarized in this section have been evaluated using a variety of measures, such as GTA surveys pre- and post- training, student evaluations of their GTAs, interviews with GTAs, observations of GTAs teaching, and more. In the following sections, chemistry GTA training programs are organized into three subsections based on the focus of the

GTA role (general training, laboratory-specific training, and training for future faculty positions). At the end of each subsection, a table is included to provide a snapshot of each training program.

### 1.9.1 General training programs for chemistry GTAs

The eight studies summarized in this subsection correspond to training programs designed to help prepare and support GTAs in their teaching roles in general. Many of these trainings are focused on building GTAs' knowledge for teaching. The articles in this subsection are organized by the length of training; the shortest is described first.

Pentecost et al.[61] described a three-day training program designed to support general chemistry GTAs in implementing more student-centered practices in their sessions. At the time of publication, this training had been implemented for a few years and had been revised to incorporate feedback from GTAs. The program was interactive in nature and included a mix of group activities and presentations. The training program included an overview of literature on teaching and learning, discussions about GTAs' prior learning experiences, reviewing general chemistry content through modeled student-centered learning techniques, and an opportunity for GTAs to practice leading a session and obtain feedback. Overall, GTAs found this training to be helpful for their teaching, but even after an increased focus on implementing student-centered teaching strategies, GTAs still reported struggling to implement these strategies when they taught their discussion sessions. The outcomes of this training program suggest that GTAs need sustained support throughout the semester to meet the expectations of the course professors when implementing student-centered teaching strategies.

A six-week chemistry GTA training program with a specific focus on building a community of GTAs, modeling innovative teaching, and helping GTAs understand their role was described by Marbach-Ad et al.[60] The training was designed as a team-taught course, which began with experienced GTAs and faculty members sharing stories about their own teaching experiences. As the semester progressed, first-year GTAs had the opportunity to share stories from their recent experiences as GTAs. The discussions following instructors' stories were focused on topics such as GTA responsibilities, making laboratory sessions memorable, the student-GTA relationship, and diverse methods for presenting material. Surveys and interviews with GTAs demonstrated that GTAs felt the training provided a welcoming atmosphere to meet other GTAs and workshop their teaching. GTAs reported that they implemented what they learned in the training, though they felt the training prepared them more for teaching laboratories than teaching discussions. The authors also investigated student evaluations of their GTAs and found that GTAs who participated in the training scored higher on measures such as effective teaching, respecting students, and being prepared than first-year GTAs in previous cohorts who did not participate in this training. This training addressed the need for GTA communities and found success in this area. However, discussion GTAs required additional teaching support.

Lang et al.[62] reported an eight-week training to support chemistry GTAs in learning about, implementing, and reflecting on best teaching practices. Experienced GTAs were a key factor in implementing this training, as they provided feedback to first-year GTAs' teaching and helped with other aspects of the training. Discussions focused on various topics, such as factors that influence student learning, pedagogical strategies to support student learning, and building confidence as an instructor. Throughout the eight weeks, GTAs completed weekly reflections on their experiences implementing topics learned in class. GTAs also observed each other teaching, which contributed to fruitful informal conversations during meetings. Survey data from first-year and experienced GTAs and field notes from peer observations demonstrated that GTAs specifically found the informal discussions to be helpful in learning about teaching practices. Experienced GTAs felt their participation in the training program supported their development of teaching skills and knowledge and their development of professional skills in conducting observations and providing feedback. The authors note that in future iterations, they will increase the number of opportunities to observe peer teaching, include discussions on more topics such as classroom management, and focus on supporting GTAs in implementing what they learn in their own teaching environment.

Richards-Babb et al.[63] designed a one-semester chemistry GTA training that was modeled after pedagogy courses for science teachers. The goal of this training was broad: to better prepare GTAs for their teaching role. The training included several activities, including (1) GTAs participated in interactive classes focused on learning about how student learning occurs, issues that teachers face, and more, (2) GTAs led presentations on different teaching methods and facilitated whole-group discussions, (3) GTAs prepared and led a review session for undergraduate students, which peer GTAs and a faculty member attended, (4) GTAs prepared a 50-minute class on a topic in organic chemistry, and (5) GTAs wrote a teaching philosophy statement, which was peer reviewed by peers and faculty. Surveys sent to GTA participants indicated that GTAs found parts (3), (4), and (5) particularly helpful. GTAs also mentioned that this training was useful for their long-term career goals.

Corrales and Komperda[64] developed a semester-long training aimed at supporting GTAs in developing their teacher and researcher identities. This study was the first to investigate the co-development of chemistry graduate student researcher and teacher identities. Guided by a community of practice theory[75] and best practices for teacher training based on pre-service teacher literature, this training provided GTAs with opportunities to reflect on their experiences in graduate school and a platform to interact with other GTAs. This training program was facilitated online due to the COVID-19 pandemic. The training started with a four-day workshop, during which most of the explicit teacher training occurred. Throughout the semester, GTAs interacted with each other via an online course management system. Each GTA gave two ten-minute talks on a research or teaching topic of their choosing and were provided feedback from peers and the course instructor. The authors conducted a case study to investigate and describe the experiences of a few of the GTA participants. They found that GTAs' research and teacher identities did develop, but to different extents for different participants. Several factors influenced GTAs' identity development, including experience in research and teaching and recognition from research advisors, course coordinators, and undergraduate students. These factors seemed to have a stronger impact on GTAs' identities than the training itself, which underscores the influence of social interactions and departmental culture on GTAs' identity development.[6]

Dragisich et al. has described both a two-week pre-semester training[57] and an advanced training course for chemistry GTAs that spans over GTAs' first year of graduate school.[58] The goal of the two-week training was to prepare laboratory and discussion GTAs for effective teaching. More specifically, the facilitators focused on ethical teaching and being authoritative in the classroom, building a positive self-image through peer review and feedback, safety in the teaching laboratory, and establishing a supportive community through a variety of social activities. This two-week training was followed by an advanced training course in which GTAs completed eleven modules over the academic year.[58] The goal of this advanced training course was to support GTAs in becoming both effective teachers and well-rounded researchers, and to help GTAs digest and implement what they learned in the two-week pre-semester training. The modules in this year-long course focused on topics ranging from ensuring equity in the classroom, learning about how people learn, compressed gas safety, and building presentation, public speaking, and scientific writing skills. GTAs were provided spaces to reflect on their own teaching styles, and facilitators emphasized building confidence in GTAs throughout the training.

In 2020, Dragisich commented on adjustments that were made to the training programs to support GTAs in the time of the pandemic.[59] Namely, the author implemented a stronger focus on skills related to wellness and building a supportive community and hired experienced graduate students as "TA training fellows" to provide opportunities for first-year GTAs to learn from their experienced GTA peers. Dragisich also added three check-ins with GTAs across the semester to help build a supportive community in the challenging time of the pandemic.

The chemistry GTA training programs summarized in this section range from three days to one year in length (Table 1.1). The authors incorporate a range of goals, such as developing research and teacher identities[64] and implementing student-focused teaching methods.[61] Findings emphasize the importance of access to a supportive GTA community and sustained support from mentors.

**Table 1.1.** An overview of research describing general training programs for chemistry GTAs.

| Citation | Training Length | Training Goals |
|---|---|---|
| Pentecost et al. (2012)[61] | 3 days | Prepare general chemistry GTAs to implement student-centered teaching |
| Marbach-Ad et al. (2012)[60] | 6 weeks | Build GTA community, model innovative teaching, help GTAs understand their role |
| Lang et al. (2020)[62] | 8 weeks | Learning about, implementing, and reflecting on best teaching practices |
| Richards-Babb et al. (2014)[63] | 1 semester | Overall preparation for teaching |
| Corrales and Komperda (2022)[64] | 1 semester | Develop GTAs' researcher and teacher identities |
| Dragisich et al. (2016)[57,58]<br>Dragisich (2020)[59] | 2-weeks pre-semester training, plus a 1-year training course | Develop GTAs' skills as instructors and researchers, support GTAs in the time of the pandemic |

### 1.9.2 Training programs for chemistry laboratory GTAs

With a shift toward student-centered teaching, GTAs are often required to lead students through inquiry-based laboratories. GTAs' struggles with implementing this type of teaching style have been documented and are summarized earlier in this chapter.[2,23,24] This has led researchers toward designing training programs to specifically support these often-under-supported laboratory GTAs.

The eight studies summarized in this section correspond to four training programs for laboratory GTAs (summarized in Table 1.2).

Bond-Robinson[48] described chemistry GTAs' PChK for teaching laboratory courses and utilized these findings to design a one-semester seminar to help chemistry laboratory GTAs develop their PChK.[49,50] Within this training, laboratory GTAs met once per week with a faculty member who led the seminar to discuss methods of interacting with students in laboratory courses. GTAs recorded some of their own teaching sessions, and those recordings were used (a) to facilitate discussion during the seminar course meetings and (b) for instructors and peers to provide feedback on each GTAs' teaching. Feedback from instructors was focused on how the GTAs identified and taught important concepts in the laboratory and how they guided their undergraduate students to understand course concepts, aligning with the four levels of PChK.[48] GTAs also reflected on their actions while managing the laboratory environment and while teaching chemical concepts through an assessment created by the researcher. This assessment was also used by the seminar instructors to measure GTAs' gains over the semester. Two additional measures were taken to evaluate the impact of this training program: seminar instructors evaluated the levels of PChK present in GTAs' session recordings toward the end of the semester, and each GTAs' students responded to a survey to assess their GTA.

GTAs who participated in this training ended the semester with higher overall ratings from their students as compared to GTAs who did not. Throughout the term, GTAs performed best on actions related to mentoring, and gained more of an understanding of their role as a laboratory manager than as a teacher. Even after this training, GTAs faced challenges when attempting to transform their chemical knowledge to help students make connections between lecture and laboratory. Findings suggest that GTAs did improve their PChK as a result of this training, but still struggled to reach the highest level of PChK. The authors conclude that continual support, nonjudgmental feedback, and explicit direction help support GTAs' in developing their PChK.

Flaherty et al.[65,66] developed another training for chemistry lab GTAs that involved a pre-semester seminar and a series of workshops throughout the semester. The pre-semester workshop was focused on building GTAs' sense of psychological empowerment to enhance their self-image as teachers. In this seminar, GTAs discussed the learning difficulties faced by undergraduate lab students, set a goal to establish meaningful learning for these students, and explored literature that documents the impact GTAs may have on their undergraduate students.

The workshops implemented throughout GTAs' first semester of teaching were guided by the theory of meaningful learning,[76,77] which states that learning involves the connection of existing prior knowledge to new concepts[76] and should include an "integration of students' affective, cognitive, and psychomotor domains of learning."[77] The training designed by Flaherty et al.[66] involved four workshops spanned over one semester in which GTAs presented recordings of their laboratory sessions, and the group of trainees discussed how that GTAs' teaching promoted students' meaningful learning in the affective, cognitive, and psychomotor domains. Each GTA recorded three of their teaching sessions, and the open discussions created a community of GTAs and their mentor which GTAs found to be helpful during their teaching experiences. GTAs' session recordings were qualitatively analyzed to describe the nature of GTAs' verbal interactions with students and the progression of each GTA over the semester.

Analysis of GTAs' recorded teaching sessions revealed that there was a lack of verbal interactions focused on chemical concepts between GTAs and their students early in the semester. As the semester progressed, the verbal interactions aligning with all three domains of meaningful learning (affective, cognitive, and psychomotor) increased in frequency.[66] GTAs also demonstrated increased psychological empowerment, with an increased sense of impact, confidence, autonomy, and self-assurance in their abilities to teach and make decisions.[65]

Mutambuki and Schwartz[67] designed and implemented a six-week training to introduce lab GTAs to best teaching and classroom practices and to support them in implementing these practices in their own classes. Training meetings focused on topics such as learning about how people learn, content knowledge and setting class goals, the philosophy of guided-inquiry and how to implement it, questioning techniques, techniques to formatively assess students, reflecting on teaching, and more. To assess the efficacy of this training, the researchers collected classroom observations and interviewed GTAs, and GTAs responded to a questionnaire that prompted them to reflect on their teaching experiences.

The GTAs who participated in this training implemented slightly over half (57%) of the professional development aspects that were covered in the training, but their implementation was gradual. Individual GTAs demonstrated variations in the aspects of the professional development that they implemented, and some faced difficulties in implementing certain aspects. The variation and difficulties observed were attributed to GTAs' individual beliefs about teaching and other contextual factors. Most GTAs overcame the difficulties they faced and continued to refine their teaching with continuous support, feedback, and reflection. Overall, GTAs found the training to be beneficial to their teaching, and results emphasize the need for continual support for GTAs.[67]

Wheeler et al.[68–71] designed and implemented a week-long pre-semester workshop plus fourteen weekly follow-up meetings throughout one semester to support general chemistry inquiry-based lab graduate and undergraduate teaching assistants (referred to generally as TAs). This training was guided by situated learning theory,[75] and TAs engaged in authentic learning opportunities that incorporated many aspects of successful pre-service teacher training. During the week-long workshop, an experienced GTA modeled inquiry-based teaching as they led first-year GTAs (who acted as students) through the laboratory experiments covered in the course. Collaboration between GTAs was encouraged through small-group and whole-group discussions about the course experiments and course logistics. During the semester, TAs received feedback from their peers and were supported by a faculty mentor. TAs were provided opportunities to reflect on their teaching and to build their content knowledge. The program designed by Wheeler et al.[68–71] has been assessed in several ways, providing a great deal of insight on how it has impacted TAs and undergraduate students. Training assessments included TA surveys administered before training and throughout the academic year, interviews with TAs, and undergraduate student surveys. Notably, Wheeler et al.[69] was the first study to investigate undergraduate student learning gains as a potential outcome of TA training.

Findings related to the efficacy of the training implemented by Wheeler et al.[68–71] show that different aspects of the training were more helpful to certain TAs (e.g., reviewing course logistics was most helpful for TAs without any teaching experience), which underscores the variability in chemistry TAs' teaching due to their prior experiences.[68] GTAs reported that completing the experiments, reviewing logistics, and the training documents were most helpful. Content-based discussions were reportedly the least helpful to TAs, although TAs' content knowledge improved after the training and teaching experiences.[68,69] TAs' beliefs about teaching and learning generally shifted from traditional ("disseminator") beliefs to facilitator beliefs, though some TAs shifted back to disseminator beliefs after teaching experience.[71] Findings related to undergraduate students demonstrated that their content knowledge increased throughout the semester, and was predicted by student demographics, not their TA. Undergraduate students who perceived their TA as being more supported also believed they learned more content.[69] Overall, this training designed to support TAs as they teach inquiry labs has been demonstrated to be beneficial to TAs, and Wheeler et al.[70] offers advice for other faculty that may be designing TA trainings in other departments.

The chemistry GTA training programs summarized in this section range from six weeks to one semester in length and proved to be beneficial in supporting GTAs during their first months as a GTA (summarized in Table 1.2). These trainings are guided by several theories, such as PChK,[49,50] meaningful learning,[65,66] and situated learning.[68–71] GTAs' teaching was shown to be impacted both by their involvement in the training programs and the context in which they taught. Additional studies investigating GTAs' context and how it impacts their teaching would provide further insight into these findings.

**Table 1.2.** An overview of research describing training programs for laboratory GTAs.

| Citation | Training Length | Training Goals |
|---|---|---|
| Bond-Robinson and Rodriques (2006)[49,50] | 1 semester (1 hour meeting per week) | Develop lab GTAs' PChK (Bond-Robinson, 2005) |
| Flaherty et al. (2017)[65,66] | Pre-semester seminar plus four two-hour workshops throughout 1 semester | Develop sense of empowerment and consider undergraduate students' meaningful learning |
| Mutambuki and Schwartz (2018)[67] | 6 weeks | Learn and implement best teaching and classroom practices |
| Wheeler et al. (2015, 2017)[68–71] | Pre-semester week-long workshop plus weekly meetings throughout 1 semester | Prepare GTAs for teaching inquiry labs |

### 1.9.3 Training programs to support GTAs for future faculty positions

While chemistry GTAs certainly face challenges when teaching their undergraduate students, another challenge is met by newly graduated doctoral students who begin positions as course professors. These roles involve similar responsibilities as GTAs, such as teaching content, managing a classroom, and grading student work, but also involve new responsibilities, such as creating a syllabus and designing lecture notes and class activities. The four trainings summarized in this subsection (Table 1.3) were designed to introduce chemistry GTAs, and often postdoctoral fellows, to some of these new responsibilities and to support them in taking on professor-like roles.

Bauer et al.[72] described a one-day clinic in which GTA and postdoctoral fellow attendees were immersed in student-centered learning activities, such as project-based guided-inquiry and jigsaw activities. The attendees reflected on their experiences with these activities in the clinic and how they may be implemented in their future courses. Results from surveys indicated that attendees felt they were better able to implement active-learning strategies, became more aware of education literature, focused more on student learning, and shifted their teaching beliefs to be closer to a facilitator. This training was short and not context-specific but provided GTAs and postdoctoral fellows with knowledge that they may integrate in their futures.

Broyer and Parr[73] described a fellowship program for both GTAs and postdoctoral fellows, in which the fellow was paired with a faculty mentor and took on some responsibilities of the course the faculty mentor taught. Fellows took part in all aspects of the class to some degree, including preparing exams and leading 30-40% of the lecture sessions throughout one semester. Fellows were also required to observe their faculty mentor during the lectures they were not leading themselves. This experience provided fellows with a window into the responsibilities required of college course instructors. Fellows were surprised about the time required to prepare lectures, the difficulty in designing original exam questions, the difficulty in managing board space during lecture, and how well they needed to understand content to teach it. Fellows enjoyed their time working with students in office hours and interactive discussion sessions and getting to be a part of a college class. Graduate students and postdoctoral fellows must apply to be a fellow and obtain permission from their research advisor to participate in this program. Thus, this training is not meant to be widely implemented in chemistry departments but likely does help prepare GTAs and postdoctoral fellows for potential future course professor roles.

Kim et al.[78] described a program that provided GTAs and postdoctoral fellows with ownership over a piece of an undergraduate class curriculum. Participants in this training worked with a faculty mentor in the summer to plan and develop a class activity, which may include modifying existing curricula, introducing new activities based on their own prior experiences, or creating something completely new. During the academic year, the GTAs and postdoctoral fellows implemented and evaluated their class activity, further providing ownership over a small portion of an undergraduate course. This program had been in place for fourteen years at the time of publication, and many of the activities designed by GTAs and postdoctoral fellows remain a part of the curriculum. GTAs and postdoctoral fellows found the support from faculty to be valuable throughout their experience, and they have found the program to be helpful in preparing for their future careers.

Finally, Charkoudian et al.[74] described a program in which GTAs work with each other and a faculty mentor to design and teach a forensics chemistry course. During one semester, the GTAs in this program developed the course, which included creating a syllabus and a course outline, designing lectures and experiments, and creating evaluation systems. During the next semester, the GTAs co-taught the course and received feedback on their own teaching from peer GTAs. The GTAs who have participated in this program found it to be helpful for their personal and professional development.

**Table 1.3.** An overview of research describing training programs to prepare GTAs for future careers in academia.

| Citation | Training Length | Training Goals |
|---|---|---|
| Bauer et al. (2013)[72] | 1 day | Overview of active-learning teaching techniques |
| Broyer and Parr (2019)[73] | 1 semester | Prepare GTAs and post docs for future career by taking on duties of a faculty mentor |
| Kim et al. (2017)[78] | Summer + 1 semester | GTAs and post docs develop, implement, and assess an activity for undergraduate courses |
| Charkoudian et al. (2008)[74] | 2 semesters | GTAs work together to design and implement an undergraduate forensics chemistry course |

## 1.10 Conclusions and recommendations for research and practice

As leaders of discussion and laboratory sessions, GTAs may influence undergraduate students' learning and retention in STEM fields,[5] and thus their abilities to teach undergraduates is a focus in chemistry education research. In this chapter, the larger body of chemistry education research on chemistry graduate students is summarized to demonstrate what we know so far about how graduate students take on their GTA role. At doctoral granting institutions, chemistry GTA training is often short or nonexistent, which leaves GTAs to rely on their prior experiences and content knowledge to inform their teaching. Researchers have demonstrated how GTAs' reliance on prior experiences can present challenges to GTAs, as their prior experiences in academic settings were often in traditional lecture-style classrooms. GTAs have demonstrated traditional beliefs about teaching and learning (e.g., that students learn best when information is clearly presented to them),[23] and have been observed teaching students in this way.[55] GTAs also believe this is one of the teaching competencies required for their role, which some faculty agree with.[21]

Although inquiry-based lab GTAs generally understand what is expected of them in these roles,[22] GTAs struggle leading inquiry-based lab sessions.[2,22,24] This is likely because GTAs lack the prior experiences and training required to teach in this way[23,24] and because this teaching style does not align with their traditional beliefs about teaching and learning. Thus, GTAs require support to learn how to teach inquiry-based labs; Mutambuki and Schwartz[67] and Wheeler et al.[68–71] have designed and evaluated training programs to address this challenge.

Despite the difficulty inquiry-based lab GTAs face, their experiences teaching inquiry-based labs have influenced the development of their self-image, beliefs about teaching and learning, and prompted reflection on their own thinking.[28,56] These findings suggest that teaching inquiry-based labs can promote teacher learning, but how this impacts their actions in the classroom, if at all, remains to be explored. Additionally, longer-term training programs may further support GTAs' teacher learning in inquiry-based contexts.

As noted above, GTAs often rely on their content knowledge to inform their teaching. It is often assumed that GTAs have the necessary content knowledge to teach introductory chemistry courses, but this is not always the case.[34,35,38] Researchers have shown that graduate students' content knowledge is more sophisticated that undergraduates', but not quite as sophisticated as faculty.[30–32] Thus, the assumption that GTAs have enough content knowledge to teach these courses should be carefully considered, and training programs should include some review of content, as in two training programs summarized above.[61,67] GTAs' content knowledge has only been studied for a limited number of topics, most of which are within the field of organic chemistry.

Because content knowledge is a prerequisite for PCK, GTAs with limited content knowledge often demonstrated limited PCK,[25–27] which may impact their ability to teach course content. However, GTAs with more experience teaching demonstrated higher levels of PCK, suggesting that this knowledge develops with experience. Studies on teaching knowledge show that GTAs can generally identify what students struggle with when learning specific content, but do not always know how to best support students.[51] Training programs designed to leverage the teaching knowledge that GTAs have already expressed may help facilitate additional development of their teaching knowledge. Similar to studies of GTAs' content knowledge, the studies on GTAs' teaching knowledge are limited to teaching laboratory,[48] thin-layer chromatography,[25] solution chemistry,[26] $^1$H NMR spectroscopy,[27] and acid-base titrations.[51] Thus, there are many opportunities for future research focused on chemistry GTAs' content and teaching knowledge for the vast number of topics covered in courses that GTAs typically teach. Additionally, grading lab reports and other student work is a common responsibility for chemistry GTAs, however, only one study has focused on the ways GTAs grade student work. There is much more to be understood about how GTAs use their disciplinary knowledge when grading assessment responses.

The training programs summarized in section 1.10 begin to address some of the concerns identified by researchers and constitute a resource for others who plan to develop chemistry GTA training in their own departments. Even GTAs who participated in these training programs demonstrated that the context in which they teach has a strong influence on their development as instructors[64,67,70] and they require sustained support from peer and faculty mentors to accomplish the goals set by course professors.[49,50,61,67]

Overall, the research summarized in this chapter provides building blocks for understanding chemistry GTAs' experiences teaching within their unique instructional context. Most of this research is focused on lab GTAs; much remains to be understood about GTAs who teach discussion sessions. Studies involving discussion GTAs may offer new insights about GTAs' teaching as they typically have more freedom in the organization of their sessions. Additionally, with just three studies involving observations of GTAs' laboratory sessions,[54,55,67] more research focused on how GTAs teach content, guide student thinking, and evaluate student learning during class would greatly contribute to the field's understanding of GTAs and can further inform training programs. While the research summarized in this chapter provides a foundational understanding of chemistry GTAs, much remains unexplored.

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# Chapter 2

# University Instructors’ Knowledge for Teaching Organic Chemistry Mechanisms

## 2.1 Initial remarks

This chapter corresponds to a study describing GTAs’ knowledge for teaching organic chemistry mechanisms. GTAs routinely teach introductory organic chemistry lab and discussion sessions where content knowledge of organic chemistry is one requisite for teaching. However, as summarized in Chapter 1, graduate students have demonstrated limited content knowledge in organic chemistry, often expressed as limited representational competence. Research on undergraduate student understanding of organic chemistry echoes this sentiment; undergraduate students struggle to interpret and utilize the many representations that communicate chemistry concepts, like curved arrows. The studies on GTAs’ PCK of solution chemistry, thin-layer chromatography, and $^1$H NMR spectroscopy (summarized in Chapter 1) demonstrate that GTAs’ content knowledge impacts their PCK. The study in this chapter focuses specifically on chemistry GTAs’ knowledge for teaching organic chemistry mechanisms, which is qualitatively compared to their content knowledge to investigate the relationship of GTAs’ content knowledge of organic chemistry mechanisms influences and their PCK of this topic. GTAs’ content knowledge and PCK are compared to that of three faculty participants with experience teaching organic chemistry, who were included in this study to theoretically represent a population with high levels of content knowledge and PCK.

This study was guided by the PCK framework, which describes teaching knowledge as a transformation of content knowledge. The PCK theory used in this chapter describes topic-specific PCK, which includes knowledge of learners’ prior knowledge, knowledge of representations and analogies, knowledge of what makes a topic difficult, curricular saliency, and knowledge of conceptual teaching strategies. This theory guided both the data collection and analysis, as the authors aimed to characterize chemistry GTAs’ PCK of organic chemistry mechanisms and to relate GTAs’ PCK to their content knowledge. In this study, GTA and faculty PCK was elicited as participants evaluated authentic student responses to organic chemistry mechanism exam questions.

Results from this study suggest that chemistry GTAs' knowledge of what makes learning organic chemistry reactions difficult—that is, interpreting representations—aligns with literature on undergraduate student learning and thus constitutes a strength in GTAs' PCK. GTA participants demonstrated limited curricular saliency, which was not entirely surprising since GTAs are rarely involved in the design of course curricula. GTA participants also demonstrated limited knowledge of teaching strategies, which seemed to be influenced by their limited content knowledge. More specifically, faculty participants noticed certain aspects of the students' responses that GTAs did not, such as overcounting electrons in transition state drawings. Failing to notice certain aspects of students' responses may cue GTAs into using certain teaching strategies that are misaligned with the student's true misunderstanding. GTA participants' knowledge of teaching strategies tended toward knowledge-telling teaching strategies, where GTAs explained the content students should understand related to the task at hand. This presents a quandary in cases when GTAs' assumptions of what students are thinking are misaligned with students' actual thinking, and thus GTAs' explanations are misaligned with students' struggles. Additionally, as mechanism questions increased in difficulty and complexity, GTAs struggled to complete the mechanism themselves. While they were still able to identify what makes the question difficult, they struggled to describe how they would respond to the student to guide them in those questions. Faculty participants did not demonstrate the same struggles, as they held the content knowledge and PCK for these types of questions.

Results from this study, including a description of GTAs' PCK and a demonstration of how GTAs' content knowledge impacts their PCK, may inform both training for chemistry GTAs and future research in this area. GTAs' strength in their knowledge of what makes learning organic chemistry mechanisms difficult can be leveraged in GTA training and staff meetings to support GTAs' learning of teaching strategies. Further, the assumption that graduate students have sufficient content knowledge to lead organic chemistry discussion and lab sessions should be carefully considered when such trainings are designed. While we investigated GTAs' knowledge of teaching organic chemistry mechanisms through task-based interviews, further research involving observations is needed to understand more completely how GTAs utilize their knowledge and navigate their shortcomings as they teach their students in their lab and discussion sessions.

This chapter first appeared as a research article in *Chemistry Education Research and Practice*, and the original publication and copyright information are provided below. The original publication was modified to adhere to Rackham dissertation formatting requirements, though no additional changes were made. Jordan Tyo assisted with parts of data collection, qualitative data analysis, and writing portions of the published article. All remaining work, including study design and the remaining data collection, qualitative data analysis, and manuscript writing were completed independently by the author.

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## 2.2 Abstract

Many recent studies document the difficulties that students experience when learning organic chemistry, often due to the complex visualization and reasoning skills required to successfully understand the ways molecules interact in specific environments. Many of these studies call on instructors to improve their teaching strategies to support students' learning of organic chemistry mechanisms, but few have focused on instructors' knowledge of organic chemistry and how they use their knowledge to teach this topic. To investigate university instructors' knowledge for teaching organic chemistry mechanisms, we utilized a task-based think-aloud interview protocol where graduate teaching assistants (GTAs) and faculty instructors assessed authentic undergraduate student responses to three organic chemistry mechanism questions. We describe this knowledge for a substitution, an acid–base, and an addition reaction. For all mechanisms, we describe how GTA participants' knowledge for teaching related to their content knowledge. This result revealed differences between GTA and faculty participants' knowledge for teaching mechanisms that were specific to features of each mechanistic task. For example, in a substitution reaction question, all faculty participants recognized and explained issues with a student's drawing

of a transition state and apparent understanding of partial bonds. These features of the student's drawing were not recognized by any GTA participants, who focused instead on the student's prior knowledge about ionic bonding. These findings qualitatively illuminate strengths and weaknesses in graduate students' knowledge for teaching which can guide how they are supported as instructors.

## 2.3 Introduction

Organic chemistry courses are some of the most difficult introductory chemistry courses for undergraduate students. To understand how to support student learning in organic chemistry, many researchers have focused on the ways students work through organic chemistry content.[1] Studies focused on representational competence have found that novice learners struggle to make the necessary connections between representations and their underlying meaning—e.g., identifying a molecular structure based on its formula.[2–4] This struggle often impacts students' abilities to mechanistically reason through a chemical transformation because students need to more deeply interpret many symbolic representations to do so. One of the most ubiquitous representations used in a chemical transformation is the curved arrow formalism, which undergraduate and graduate students reportedly struggle to fully understand,[5–7] with the exception of some students enrolled in a patterns-of-mechanisms organic chemistry curriculum and flipped course format.[8,9]

While many studies have focused on undergraduate student and graduate student learning of organic chemistry, the same attention has not yet been paid to the instructors of these courses. At large research institutions, graduate students are hired as graduate teaching assistants (GTAs) to teach the lab and discussion classes that accompany large introductory chemistry courses. Through these teaching assistantships, GTAs often spend more instructional time with undergraduate students than professors.[10] At these types of institutions, it is often assumed that graduate students enter graduate school with sufficient content knowledge from their undergraduate studies and that content knowledge alone is sufficient for adequate teaching. However, it has been shown that some graduate students lack fundamental chemistry knowledge[5,11] and, while content knowledge is a prerequisite to the development of teaching knowledge, high levels of content knowledge do not guarantee high levels of teaching knowledge.[12–15]

The goal of this study was to investigate GTAs' knowledge for teaching organic chemistry mechanisms to (1) better understand how GTAs address the challenges and alternative conceptions that their students are known to face and (2) inform training designs to better support GTAs in their instructor role.

## 2.4 Background

### 2.4.1 Learning to reason mechanistically

Introductory organic chemistry courses are required for many different undergraduate majors, and in these courses, students learn many foundational chemistry concepts and problem-solving techniques. One of the most challenging tasks in the organic chemistry curriculum is using chemical knowledge to propose mechanistic transformations correctly. While a consensus definition of mechanistic reasoning has not yet been achieved, practitioners and researchers have worked toward a common definition.[16] For the context of this study, our definition is similar to Watts et al.,[17] drawn from Bhattacharyya.[16] Students with successful mechanistic reasoning skills are able to describe what changes in a reaction, how the changes happen, and why the changes happen. This skill involves interpreting symbolic representations of molecules to understand underlying behaviors (e.g., which molecules act as acids or bases, possible resonance structures, partial or formal charges), the role of the molecules included (e.g., reagents, solvents, catalysts), and how each of these entities interacts with the others to produce appropriate products. Reasoning through how entities interact involves considering the logical movement of atoms and electrons (represented by curved arrows) and the formation of intermediate structures and products. Note that this definition does not include a connection to the energetics of reactions, which is a requirement of causal mechanistic reasoning.[18] To master the ability to propose mechanistic transformations, students must first develop the necessary chemical knowledge (e.g., understanding valence shells, electronegativity, bond polarity, etc.). As they learn to draw on this knowledge, they must also learn to interpret representations used in organic chemistry (e.g., reaction arrows, resonance contributors, etc.) to create a mental representation and make meaning of the transformation of interest.[16] This is no small task but results in students strengthening their problem-solving skills.[2]

Many researchers have focused on investigating how students undertake the pieces of this task (i.e., interpreting representations) and the task as a whole (i.e., completing a mechanism).[1]

Symbolic representations like elemental symbols, curved arrows to indicate electron flow, and plus and minus symbols to indicate charge are fundamental components of communicating chemistry. To understand how novices (undergraduate students) and experts (practicing chemists) differ in their understanding and use of chemical representations, we turn to research on representational competence.[19–21] Kozma and Russell[20] found that undergraduate students struggle to utilize multiple representations, so their understanding and communication of chemistry are hindered as they rely primarily on surface features of representations, findings that are consistent with organic chemistry-specific studies.[4,5,7,22,23] On the other hand, practicing chemists can utilize multiple representations, swiftly moving within and across them, and can communicate chemistry using symbols to represent underlying processes and entities.[19,24] Developing representational competence is key for success in chemistry, as students' problem-solving abilities are hindered if they cannot translate between different representations (e.g., drawing a molecule based on a structural formula).[2] Furthermore, in a case study of seven undergraduate students enrolled in organic chemistry, Anderson and Bodner[4] described one student who struggled to attribute useful meaning to chemical symbols. He was a successful chemistry student until it was necessary for him to consider the underlying meaning of the symbols used to represent mechanistic transformations, further pointing to the conclusion that representational competence is key for success in organic chemistry.

As Anderson and Bodner[4] indicate, reasoning through a mechanism is incredibly difficult without understanding what chemical symbols represent. Research focused on undergraduate students' ability to reason mechanistically through a chemical transformation overwhelmingly indicated that students could complete mechanisms and use the arrow-pushing formalism without understanding what the curved arrow symbols represent.[5,6,25,26] Students often rely on memorization; they categorize mechanism types in their minds and follow the patterns blindly. This tendency allows students to correctly reproduce mechanisms without understanding underlying causes.[27,28] When students approached reactions unfamiliar to them, they sometimes proposed mechanistic steps that were productive but chemically inaccurate.[5,6,18] When students considered underlying properties, they often focused on one feature (e.g., charges or resonance) to explain chemical behavior.[25,26]

While many studies have demonstrated students' mechanical and meaningless use of mechanistic arrows, there are few cases were students demonstrated an understanding of what mechanistic arrows represent.[8,9,17] Students enrolled in a patterns-of-mechanisms organic chemistry curriculum with a flipped course format, where the curriculum specifically addresses the symbolism of mechanistic arrows, attributed meaning to mechanistic arrows when solving familiar and unfamiliar mechanisms.[8,9] Results from these studies indicated that the modified curriculum in which students learn about the underlying meaning of mechanistic arrows positively impacts their understanding. In another study by Watts et al.,[17] students enrolled in a more traditional curriculum were asked to specifically describe steps of a mechanism in writing. Of these students, 85% explicitly described the movement of electrons in a given mechanism. Webber and Flynn,[8] Galloway et al.,[9] and Watts et al,[17] all demonstrate that undergraduate students are capable of attributing meaning to mechanistic arrows but need specific instruction to do so.

In a study by Bode and Flynn,[22] 700 student responses to mechanism exam questions were analyzed to determine problem-solving strategies commonly used by successful and unsuccessful students. They identified six strategies that were common in successful students' problem-solving strategies, but rare among unsuccessful students: identifying new bonds in the target molecule, identifying which atoms are added to the starting material, identifying key regiochemical relationships, mapping starting material atoms to the product, using a partial or complete retrosynthetic analysis, and drawing reaction mechanisms. The degree to which instructors influence students' use of these strategies has not been studied. Bode and Flynn[22] suggest that research on the instruction of organic chemistry mechanisms is needed to understand another dimension of students' understanding of this topic.

### 2.4.2 Instructors' knowledge for teaching

While researchers have not yet investigated GTAs' knowledge for teaching organic chemistry mechanisms, others have investigated various facets of GTAs' experiences. In a qualitative study focused on the teaching knowledge and identities of chemistry GTAs, GTAs reported very few opportunities to develop as instructors. They were often discouraged from doing so.[29] This discouragement, along with the pressure to conduct good research, caused GTAs to identify as tutors or lab managers, which inhibited self-investment in their teaching role. Although there is an assumption that graduate students have the content knowledge necessary to teach introductory chemistry courses, GTAs reported struggling with the content in this study.[29] Other studies have also documented the specific ways GTAs struggled with certain content.[5,27] Studies of GTAs' pedagogical content knowledge (PCK) relevant to organic chemistry, specifically of thin layer chromatography[30] and 1H NMR spectroscopy[14] demonstrated that GTAs had high levels of content knowledge. Yet, GTAs exhibited generally lower levels of PCK, further indicating that even with appropriate content knowledge, instructors need spaces to develop their PCK.[31].

In a study comparing GTAs' and high school teachers' content knowledge and TS-PCK of high school organic chemistry content, GTAs demonstrated higher levels of content knowledge and lower (but not significantly lower) levels of TS-PCK than high school teachers.[32] These results suggest that GTAs can develop TS-PCK even with their relatively limited teaching experience. Further, this study underscores the importance of studying the development of knowledge for teaching among different types of instructors and contexts. Given that many studies have demonstrated how students grapple with organic chemistry mechanisms,[1] that GTAs often spend more instructional time with undergraduate students than professors,[10] and that GTAs themselves struggle with organic chemistry mechanisms,[5] we sought to characterize GTAs' PCK of organic chemistry mechanisms.

## 2.5 Theoretical perspective

Since its conception by Shulman in 1986,[12] PCK has gained traction in education research communities across the disciplines. PCK refers to the special knowledge that teachers possess at the intersection of content knowledge and pedagogical knowledge. With strong PCK, teachers can transform content in a way that enhances student learning of the particular content. In the years following Shulman's introduction of PCK, many conceptions of PCK were published, with some of them being discipline-specific.[13,33–36]

The number of different frameworks has prompted science PCK summits, the most recent in the year 2016.[36] This summit resulted in the reformed consensus model of PCK, which detailed several realms of PCK and the interactions between them.[36] Most central is "enacted PCK," which refers to the actions teachers take to plan, teach, and reflect on their teaching. This domain directly interacts with "personal PCK," the domain that includes teachers' own pedagogical content knowledge. Teachers draw upon their personal PCK to inform their enacted PCK. Both personal and enacted PCK are situated within teachers' individual contexts, implying that these two realms of PCK are influenced by the teachers' experiences, the classroom environment in which they teach, and the students that make up their class. The third PCK realm is "collective PCK," which includes PCK constructed by many science educators and researchers. It is defined by Hume et al.[36] as "a specialized knowledge base for science teaching that has been articulated and is shared among a group of professionals, which is related to teaching that particular subject matter knowledge to particular students in a particular learning context" (p. 88). It is within this realm that Shulman's original conception of PCK belongs.[12,37] The study presented herein, in which we investigate the PCK of individual university instructors, is situated within the realm of personal PCK.

Because we are investigating PCK of a particular topic—organic chemistry mechanisms—we used the topic-specific PCK (TS-PCK) framework defined by Mavhunga and Rollnick[35] to inform our data collection and analysis. This framework acknowledges that an instructor's PCK within a discipline (e.g., chemistry) can vary depending on the topic (e.g., stoichiometry versus reaction mechanisms). Studies have reported the topic-specific nature of PCK,[38] and this framework has been used to analyze chemistry instructors' PCK for many different topics like chemical equilibrium,[35] thin-layer chromatography,[30] and 1H NMR spectroscopy.[14]

This framework for TS-PCK includes five components: knowledge of (1) learner's prior knowledge, (2) what makes a topic difficult to learn, (3) representations, (4) curricular saliency, and (5) conceptual teaching strategies.[35] Learner's prior knowledge refers to the knowledge students have or do not have that is relevant to learning a new concept, including alternative conceptions about relevant content. Knowledge of what makes a topic difficult includes the ability to identify specific concepts that are difficult for students to understand. Knowledge of representations refers to instructors' knowledge for representing content, including examples, illustrations, demonstrations, etc. and the benefits and limitations of those representations. Curricular saliency refers to the ability to arrange various concepts within a curriculum and to understand which concepts are most central and should be covered in-depth and which concepts are more peripheral. Knowledge of conceptual teaching strategies includes instructors' knowledge of instructional strategies to address particular alternative conceptions or areas of difficulty and teach important concepts.[35] Using this framework, we have defined the following research question to guide our study in investigating graduate students' TS-PCK of organic chemistry mechanisms: What is the nature of chemistry graduate teaching assistants' knowledge for teaching organic chemistry mechanisms?

## 2.6 Methods

### 2.6.1 Context

This project was conducted at a large, public, research-intensive university in the Midwestern United States. GTA participants were recruited from a first-semester organic chemistry course. This course consists of a one-hour lecture three days per week and an optional one-hour discussion section one day per week. Lectures are taught by professors, lecturers, or post-doctoral fellows and have hundreds of students, while discussions are taught by graduate students and have 20–30 students. An in-house textbook accompanies course lectures, which follows a fairly standard curriculum, as seen in other studies.[39] Assessment is based solely on scores from three midterm exams and one final exam. Students primarily use a workbook containing sample problems from previous years' exams to study and become accustomed to the exam format. Most students in the course are first- or second-year students. Few students in the course are chemistry majors; the majority of students are pre-medicine.

Graduate students are hired as teaching assistants for this course, which serves as a source of funding via a graduate teaching assistantship. Teaching assistants receive a two-day teacher training during summer orientation before obtaining their specific teaching assignments. Weekly staff meetings are held throughout each semester, during which the instructors and GTAs discuss the topics for the week, anticipate student questions, and discuss the logistics of the course. The instructors may provide guidelines and suggestions to support GTAs in their discussion sections, but the structure of each discussion section is ultimately determined by the GTA teaching that section.

### 2.6.2 Participants

We interviewed 17 graduate students with a range of teaching experience. In the fall of 2018, incoming graduate students were emailed to participate in this study. Because content knowledge is a prerequisite for PCK,[14,35,37] we specifically invited graduate students who intended to join organic chemistry research laboratories with the assumption that they are more likely to possess a foundation of organic chemistry content knowledge than their peers in other subdisciplines (e.g., inorganic chemistry). At this time, we interviewed seven graduate students to capture TS-PCK of novice university instructors. To capture TS-PCK from a more experienced population, we invited graduate students who had taught organic chemistry discussions to participate. All experienced GTAs had held a teaching assistantship position for at least two semesters, though most experienced GTA participants had been teaching for three or more semesters. Four graduate students agreed to participate. After a preliminary analysis of the first eleven interviews, we determined that we had not reached saturation. Three additional experienced graduate students were interviewed in April of 2019, and three additional incoming graduate students were interviewed in September of 2019. Saturation—no new themes appeared in preliminary analysis—was reached with this set of 17 interviews. Seven of ten incoming GTA participants and six of seven experienced GTA participants had prior teaching experience during their undergraduate studies.

We also interviewed three faculty members who had taught the organic chemistry lecture course to capture an upper-bound of university instructors' PCK of organic chemistry mechanisms. One faculty participant had taught the organic chemistry lecture course five times, and two faculty participants had taught the course over twenty times.

### 2.6.3 Interview protocol

The think-aloud interview protocol used in this study was developed to elicit our participants' TS-PCK of organic chemistry mechanisms. As such, we initially chose three organic chemistry mechanism questions that covered a range of reaction types—substitution, acid–base, and addition. For each question, participants filled out a blank exam question themselves, compared their answer to an answer key (see Supporting Information), and then assessed an authentic undergraduate student response pulled from a past exam to the same question (Figures 2.1, 2.3, and 2.5). Participants were asked to think-aloud as they completed each task to capture their thought processes.[40] When participants were presented with the authentic undergraduate student response, they were asked to give their overall impression and to respond to specific questions:

1. Was this student correct? Why or why not?
2. What makes this problem difficult?
3. What thinking on the part of the student may have led to this response?
4. How would you respond if one of your students showed this answer to you?

The questions in our interview protocol specifically probed participants' knowledge of what makes the problem difficult (question 2), knowledge of learners' prior knowledge (question 3), and knowledge of teaching strategies (question 4). Although knowledge of representations and curricular saliency are not specifically probed by our interview protocol, the components of TS-PCK are interconnected;[41] it is often impossible to isolate only one component and eliminate the potential to elicit others. So, while the interview protocol specifically elicits participants' TS-PCK of what makes the topic difficult, learners' prior knowledge, and teaching strategies, we were also able to elicit and identify the remaining components of TS-PCK in some interviews. Moreover, by assessing student responses, participants offered approximations of some of the cognitive work involved in their teaching. Through these approximations, we are better able to understand TS-PCK as a whole, rather than solely as its individual components.[42] The authentic undergraduate student responses were chosen to demonstrate what we know students struggle with based on previous research focused on student learning of organic chemistry.[6,20,25,43–46] More detail regarding these student responses is included in the results section.

Pilot interviews were conducted with an incoming graduate student, a graduate student who taught organic chemistry discussion, and a postdoctoral fellow with a PhD in organic chemistry who taught organic chemistry lecture. The pilot interviews were conducted to ascertain that the chosen mechanism questions were representative of the content taught in introductory organic chemistry and that the student responses to the mechanism questions were representative of student responses in the course. After the pilot interviews, one question was removed because all pilot interview participants noted that its content was not commonly discussed in introductory organic chemistry. It was replaced with another question that was more representative of topics covered in the course (an acid–base question).

For each interview, audiovisual data was recorded, and all written work was collected at the end of the interview. The audio data were transcribed verbatim using a secure online service and served as our primary sources of data. Visual recordings were used as a supplementary source of data for when participants used vague language. For example, if a participant said, "this atom would be the most basic," we would use the visual recordings to identify the atom to which they were referring. Participants' written work was scanned, stored digitally, and was used in a similar manner as the visual recordings. IRB approval was obtained for this study, and all participants gave informed consent to participate. All data were anonymized, and participants were given pseudonyms.

### 2.6.4 Data analysis

Analysis of the audiovisual interview data was approached with a theoretical grounding in the TS-PCK framework.[35] All transcripts were qualitatively analyzed using the NVivo 11 Pro software for participants' TS-PCK of organic chemistry mechanisms through provisional coding methods,[47] where data were coded using predetermined codes. Namely, we coded for the components of TS-PCK described above, including learner's prior knowledge, what makes a topic difficult, curricular saliency, representations, and conceptual teaching strategies. Transcripts were coded at the paragraph-level, and one paragraph could receive multiple codes if warranted. The first author coded a subset of interviews and slightly adjusted the codebook. More specifically, we noted that most participants' responses to the question, "How would you respond if one of your students showed this answer to you?" did not elicit conceptual teaching strategies that aligned the Mavhunga and Rollnick[35] definition: knowledge of instructional strategies to address particular alternative conceptions or areas of difficulty and to teach important concepts. Many responses, for example, followed a knowledge-telling format in which the participant described the content they would tell the student to correct their answer. Rather than leaving these responses uncoded, we adjusted this code to be named "teaching strategies," defined as any method of supporting the undergraduate student in correcting their response. Our codebook is included in the supporting information.

The first and second authors met to discuss the final codebook, and then independently coded 20% of the data. The first two authors then compared their codes, discussed any discrepancies, and used differences to refine the codebook. The first two authors then independently coded an additional subset of 20% of the data. Inter-rater reliability (IRR) was calculated with this subset of data to determine the degree to which the codebook could be consistently applied to our data set. IRR was determined using a modified Cohen's kappa, the Fuzzy kappa statistic, which allows for more than one code to be applied to a single unit of analysis.[48] Our interrater reliability value (0.84, Fuzzy kappa) indicated a consistent implementation of our coding scheme.[49] The first and second authors then coded each of the remaining interviews.

Coded excerpts underwent a second round of analysis during which the TS-PCK for each subset of participants (incoming GTAs, experienced GTAs, and faculty) was summarized for each reaction question. Common elements of TS-PCK were identified across all participants and within each subset of participants.

## 2.7 Limitations

There are several important limitations to discuss regarding our participant population and our interview protocol. First, all participants were from one university, limiting the transferability of our results to other contexts. Graduate students and professors volunteered to participate in this study, which introduces the possibility of self-selection bias. Furthermore, the desire to include authentic student responses to organic chemistry mechanism questions in our interview protocol limited the pool of organic mechanism questions to those used as exam questions at this particular university. All chosen questions were from the first-semester organic chemistry course. While instructors at this university are familiar with the question format, it may not reflect question formats used at other universities. The interview format—focused on exam questions—may have unintentionally elicited specific components of TS-PCK more so than others. More specifically, exams are meant to be challenging and to measure students' knowledge. Thus, focusing on exams during interviews may have prompted participants to focus more on their knowledge of what makes a topic difficult and learner's prior knowledge than on representations, curricular saliency, or teaching strategies. Because all components of PCK are interconnected,[41] we were able to elicit all components of TS-PCK with the protocol described above. However, additional research focused on GTAs' knowledge of representations, curricular saliency, and teaching strategies is needed to describe these components in a more complete manner. Additionally, asking participants to describe what made the problem difficult after showing the undergraduate student responses may have influenced participants to focus specifically on what challenged the particular student. Should this study be repeated, we recommend asking this question prior to showing the undergraduate response, and about the reaction type in general. Finally, the use of interviews provided insight into participants' conceptions and knowledge for teaching but did not provide direct evidence for the practices that teachers use in their classroom.[50] Further research through observations is needed to investigate the actions GTAs take as they teach organic chemistry discussion courses.

## 2.8 Trustworthiness

While the generalizability of our results may be limited by our participant population and the specific organic chemistry mechanism questions used in the interview protocol, we strove to maintain the trustworthiness of our results through multiple facets.[51] First, we have provided a detailed description of our participants, interview protocol, and analysis methods. Second, at the end of each interview with faculty members, we asked (1) if the mechanism questions presented were typical for their course and (2) if the undergraduate student responses were representative of how they would expect their students to respond. All faculty participants voiced that the substitution and addition reactions aligned well with the types of questions they ask on their written exams in their classes. The acid–base reaction, however, was not met with as much agreement—faculty noted that it was a fair question, but they did not like it since the reaction is unfavorable (this is further described in the results section). Faculty overwhelmingly agreed that the student responses for all three questions were representative of the most common mistakes made by their students.

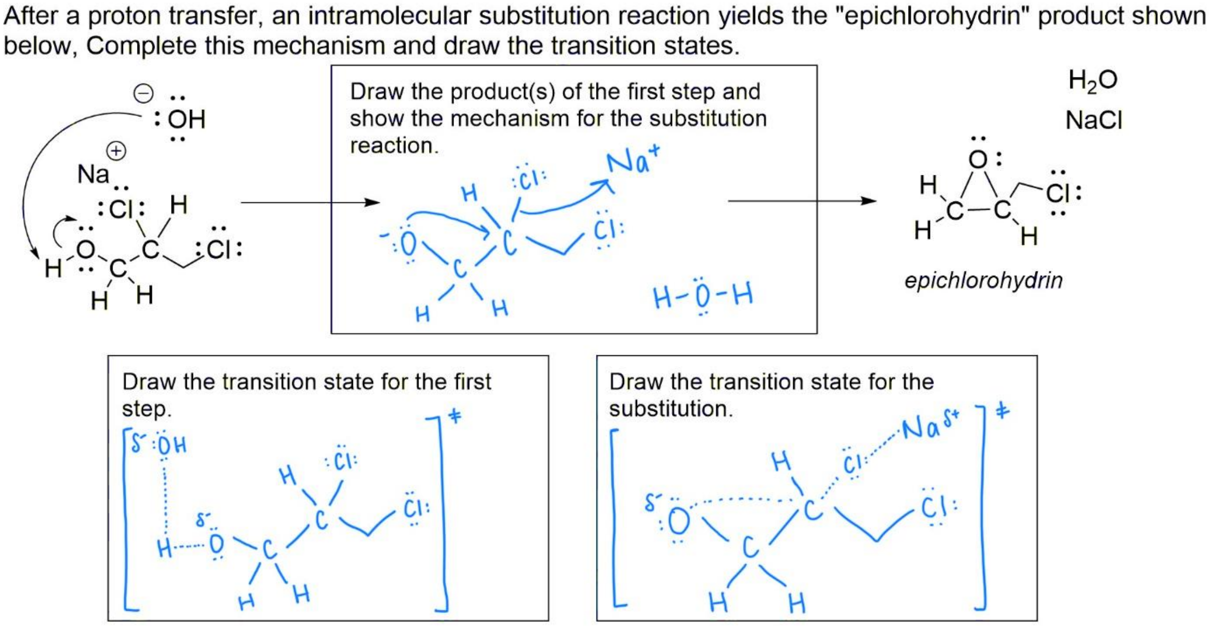
After all the interviews were conducted and all the data were analyzed, we presented our results describing GTAs' TS-PCK to two faculty participants. We intended to evaluate the degree to which our results were consistent with their experiences as organic chemistry instructors who often teach alongside chemistry GTAs. This check was completed through a questionnaire using the Qualtrics software. For each mechanism question, the faculty members were presented with the undergraduate student response to the question. They were given space to record how they would expect an organic chemistry GTA to respond to this undergraduate student. They were presented with our results describing the organic chemistry content knowledge and TS-PCK for our GTA participants. They were then asked to comment on whether the results were surprising to them and if they would expect GTAs to say anything else to this student. The outcomes and perspectives gained from this process are reported in the following sections.

## 2.9 Results and discussion

### 2.9.1 Question 1: Substitution reaction

The substitution reaction question (see Figure 2.1) prompted students to draw the product of a proton transfer reaction given the starting material and curved arrow mechanism of the proton transfer, then to draw the curved arrow mechanism for the substitution reaction that yields the given product. The exam question also prompted students to draw the transition state for each step. The answer key is provided in the supporting information, Figure 2.7. All participants except for one incoming GTA answered this question correctly. A few incoming GTA participants were unfamiliar with drawing transition states but were ultimately able to answer the question correctly. Both of the faculty members who reviewed our results were unsurprised that some GTAs struggled with drawing the transition states because, as one faculty member said, they "likely have to dust off the rust of old knowledge."

The undergraduate student response selected for the substitution reaction question (Figure 2.1) represents students with a misunderstanding of the nature of ionic bonds or how to represent their formation. In the first box, the student correctly drew the product of the first proton transfer step. When drawing the curved arrow mechanism for the intramolecular substitution reaction, the student incorrectly drew a curved arrow from the carbon–chlorine bond of the intermediate to the sodium ion, indicating a covalent bond forming between sodium and chlorine. The student response also had errors in their transition states. In both transition states, the student represented the electrons that form bonds twice, both as a partial bond and as a lone pair. In the second transition state, the student showed a partial bond between the chlorine and sodium, a partial-positive charge on the sodium, and no charge on the chlorine. From inspecting this undergraduate


After a proton transfer, an intramolecular substitution reaction yields the "epichlorohydrin" product shown below, Complete this mechanism and draw the transition states.

Draw the product(s) of the first step and show the mechanism for the substitution reaction.

Draw the transition state for the first step.

Draw the transition state for the substitution.

**Figure 2.1.** Undergraduate student response to the substitution reaction question.

student's response, it is possible that this student understands that sodium chloride is an ionic compound but holds an alternative conception about the curved arrow mechanism and what it represents, and/or that this student understands the curved arrow mechanism but does not recognize the ionic nature of the sodium chloride bond.

**Learner’s prior knowledge.** Participants suggested different reasons for the undergraduate student's response to the substitution reaction question, demonstrating their TS-PCK. When considering the learner's prior knowledge, eleven GTA participants (five of ten incoming GTAs and six of seven experienced GTAs) and all three faculty members believed the student thought that the sodium chloride bond was covalent instead of ionic. For example, when discussing why the student may have drawn the incorrect curved arrow from the carbon–chlorine bond to the sodium, an experienced GTA explained, “Maybe that assumption that this is a covalent bond, then they drew the arrows to be consistent with that.” This GTA concluded that the student's errors stemmed from a lack of knowledge of sodium chloride bonding ionically and an assumption that the bond was covalent. This was a common claim among participants, and while Taber[52] found that some chemistry students view ionic bonds as special links between specific ions and thus perceived them as molecules, further research has not indicated that students struggle to differentiate between ionic and covalent bonds.[53]

Alternatively, four GTA participants (three incoming GTAs and one experienced GTA) thought that the student knew that sodium chloride is ionic and tried to use curved arrows to indicate the formation of an ionic bond. For example, an incoming GTA stated, “In my perspective, they probably had that knowledge that these form an ionic bond, and they'll come together. So, this is then trying to show that this chlorine is about to go to that sodium.” This notion is consistent with previous studies of undergraduate students’ use and understanding of the curved arrow mechanism, which suggests that students draw curved arrows with little to no meaning associated with their use,[6] however, it is concerning that only four participants considered this, all of whom were GTAs.

Interestingly, all three faculty participants, but none of the GTAs, noticed a specific feature of this student's drawn transition states that indicated another alternative conception. In many instances, the student overcounted the electrons around a specific atom. Faculty participants noticed that when the student drew transition states, they sometimes drew too many electrons on atoms that had partial bonds. For example, in the transition state for the first step of this reaction, the student drew three sets of lone pair electrons around the hydroxide oxygen and drew the partial bond between that oxygen and the hydrogen on the other molecule. One faculty participant said:

> *It looks like they double counted the electrons. […] That would make me think that they don't quite understand what this partial bond is indicating. They're showing that it means a bond is forming or a bond is breaking, but they don't know what those dots are corresponding to, other than that there's going to be a bond there, not that those might be electrons, which is the way I usually teach it.*

Our faculty participants noted that this indicates that the undergraduate student lacks an understanding of partial bonds and the electrons that form those bonds. They specifically interpreted this to mean that though the student knew that partial bonds indicate a bond breaking or forming, they did not understand how partial bonds relate to electrons.

One of the faculty members that reviewed our results specifically noted that they were surprised that GTAs did not notice this as well. Another stated that partial bonds are an extension of the curved arrow formalism; curved arrows show the movement of electrons to break or form bonds, and partial bonds drawn in a transition state demonstrate a snapshot of those bonds breaking or forming. As such, it was not surprising that GTAs did not notice this misrepresentation in the undergraduate student's work, given that graduate students have limited conceptions of the curved arrow mechanism as well.[5] The limitation described here in GTAs' ability to recognize potential gaps in students' prior knowledge could be a result of the limitations in some of the GTAs' content knowledge, though for others it is the result of limitations in PCK.

**What makes the topic difficult and representations.** When considering what makes this question difficult, participants drew on their knowledge of representations. Eight GTA participants (three incoming GTAs and five experienced GTAs) and two faculty participants noted that the representation of the sodium chloride product made the problem more difficult for students. As one incoming GTA stated, "I think what makes the problem difficult, well, especially in this person's case, is that the product doesn't show sodium chloride as an ionic bond." This GTA and other participants recognized that having ionic products shown without formal charges made the problem more difficult for students since its ionic nature is less obvious. Similarly, Kozma and Russell[20] noted that undergraduate students primarily focus on surface-level features of representations. In this case, the ionic nature of sodium chloride was not explicitly represented in this exam question.

**Curricular saliency.** Four GTA participants (one incoming GTA and three experienced GTAs), along with two faculty participants, demonstrated curricular saliency when referencing how ionic and covalent bonding is taught in the organic chemistry course. More specifically, participants noted ionic bonds are not reviewed as much as covalent bonds in the class. An incoming GTA explained, “And maybe [ionic bonding is] not reviewed a lot in my experience, always, in [organic chemistry I]. So maybe by the time they got to the exam, they were not focused on that this would be an ionic bond.” This GTA knew that ionic bonding is not covered heavily in this course, so they reasoned that undergraduate students were not thinking about whether the sodium chloride bond was ionic. They reasoned that this led the undergraduate student to consider sodium chloride as a covalent molecule and draw the corresponding curved arrow. One of the faculty members that reviewed our results agreed that ions do not play as big of a role as covalent molecules in the course, but ions are emphasized when they are present because of that limited role. The other faculty member, however, noted that this undergraduate student might have overgeneralized examples of open-shell Lewis acids to the sodium chloride case. Overall, there is little consistency in our GTA participants’ curricular saliency. While this result is not surprising given that GTAs are rarely given opportunities to provide input in course curricula and thus may rarely think critically about the content or sequence of a curriculum, it may be due to the nature of our interview protocol—we did not specifically probe for participants’ curricular saliency.

**Teaching strategies.** Participants’ knowledge of teaching strategies to support this particular undergraduate student in correcting their mistake was limited and inconsistent across participants—most of the teaching strategies were only reported by one or two participants. Thus, we are unable to report specific teaching strategies that were consistent across multiple participants. However, through further inductive analysis, we identified participants' responses to the interview question, “how would you respond to a student that showed this to you?” could be arranged into three categories: no teaching strategy, a knowledge-telling teaching strategy, or an activity-based teaching strategy. Figure 2.2 provides the distribution of teaching strategies across our participant groups.

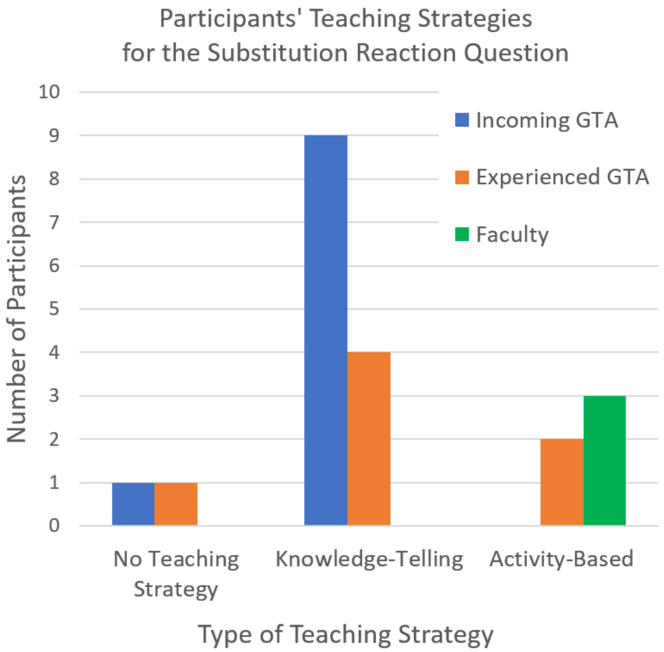


**Figure 2.2.** Participants' teaching strategies for the substitution reaction question.

Only two participants (one incoming GTA and one experienced GTA) did not provide a teaching strategy for this question. One of them did not recognize the error in the undergraduate student response and thus did not provide a teaching strategy. Thirteen participants presented knowledge-telling teaching strategies (nine incoming GTAs and four experienced GTAs), in which they described the knowledge that they would tell the student to help them without asking the student questions or inquiring about their thinking. For example, when asked how they would respond to this student, an incoming GTA said, "I would say that your indication that the covalent bond is formed between chlorine and sodium is inaccurate… Otherwise, it's correct. You should just draw the chloride being a free ion, and sodium being a free ion." Two experienced GTA participants discussed an activity they would have their students complete to guide them to the correct answer. For instance, one experienced GTA said they would point to the sodium ion and ask the student, "What do you know about this ion? What can you tell me about the sort of bonds that it likes to make or not thereof, and hopefully guide them to getting the correct answer themselves." As demonstrated in Figure 2.2, incoming GTAs primarily provided knowledge-telling teaching strategies, with just one incoming GTA not reporting a teaching strategy. Experienced GTAs were distributed across the three groups, with over half in the knowledge-telling group, two in the activity-based group, and one with no teaching strategy. All three faculty provided a teaching strategy involving an activity. One faculty pointed at the sodium chloride product and said,

> *I'd go right to there and have the student explore the business of an ionic compound and so, if there's a bond there, what is the nature of the bond? And then push back onto [the incorrect curved arrow] to say, what is that arrow telling me? Where is that pair of electrons in the structure of the ionic compound?*

Studies have reported that developing knowledge of conceptual teaching strategies is the most difficult component of PCK as it requires knowledge from the other components of PCK.[54] Furthermore, studies have shown that PCK develops with experience.[30,55,56] Our results echo these sentiments, as the majority of our GTA participants provided a knowledge-telling teaching strategy, and our participants with more experience show evidence of having sophisticated knowledge of teaching strategies.

Knowledge-telling teaching strategies alone are rarely effective at promoting students' conceptual understanding of a topic.[57] The undergraduate student response to the substitution reaction question provides a valuable example of the importance of drawing out students' knowledge through an activity-based teaching strategy. As noted above, the student's alternative conception leading to their response could be that sodium chloride is a covalent compound, that curved arrows are used to show the formation of ionic bonds, or some other alternative conception that was not discussed by our participants. If an instructor assumes this student thinks sodium chloride is a covalent compound and provides a knowledge-telling teaching strategy to address this and help the student answer the question correctly, the instructor could be misidentifying the gap in the student's knowledge. Using an activity to elicit the student's prior knowledge would allow the instructor to better support this student in learning this fundamental chemistry content. Ideally, instructors should support students through an activity-based teaching strategy, but here, it is only the case for five of our twenty participants—three of whom were faculty members. Given GTAs' role in undergraduate education, this indicates the importance of placing focus on the development of GTAs' teaching strategies during instructor training.

### 2.9.2 Question 2: Acid-base reaction

The acid–base reaction question (see Figure 2.3) provided starting materials and prompted students to draw the curved arrow mechanism and products for a proton transfer. The prompt also reminded students to show the best resonance contributor when more than one is possible. The answer key is provided in the supporting information, Figure 2.8.

This problem was challenging for our participants. In general, the proton transfer reactions possible with the given starting materials are quite unfavorable, with the equilibrium lying to the left. Faculty noted that they did not like this question for that reason. Indeed, we urge readers not to use this task as an assessment in their own teaching contexts for the same reason. Nonetheless, including this question proved to be informative because participants needed to consider multiple effects on basicity to complete the mechanism, which is a major challenge for both undergraduate and graduate chemistry students.[43–46,58] Furthermore, it is not uncommon for imperfectly written questions to arise in discussion sections, during which GTAs are expected to teach. For the acid–base question, three GTA participants chose the most likely oxygen atom (C) as the most basic atom. One of whom confidently stated:

> *I mean, [oxygen C is] the most basic one there out of all of those. So, if you think about it, [oxygen A] is an* $sp^2$ *oxygen, [oxygen B] is* $sp^2$ *oxygen localizing pair, and [oxygen C is an]* $sp^3$ *oxygen that's not delocalized into anything, and so that's gonna have the highest basicity, so that's definitely gonna take the proton*.

This GTA demonstrated how they thought through this mechanism by considering the hybridization of the three oxygen atoms. Very few GTA participants mentioned hybridization during the interview when responding to this question, which is consistent with previous studies on undergraduate students' understanding of acid–base chemistry.[44–46] When reviewing the results for this part of the interview, one of the faculty members mentioned that this type of problem is

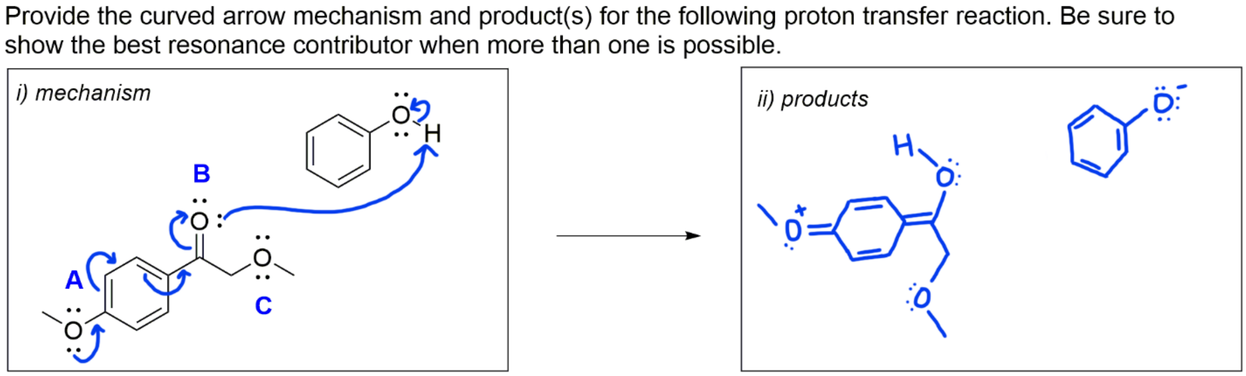

Provide the curved arrow mechanism and product(s) for the following proton transfer reaction. Be sure to show the best resonance contributor when more than one is possible.

**Figure 2.3.** Undergraduate student response to the acid–base reaction question. Note: the letters A, B, and C were added to this figure by the authors to enhance readability; they were not included during data collection. Note that this reaction is not favorable and is not intended to be replicated as an example of an ideal assessment.

difficult for undergraduate and graduate students because (1) acid–base chemistry is challenging in and of itself, and (2) there is a tendency to apply rules (e.g. resonance decreases pKa), which leads them to make quick assessments rather than using the tools provided (e.g., the pKa table).

Ten of our GTA participants (five incoming GTAs and five experienced GTAs) chose the carbonyl oxygen (B) as the most basic site and drew the products accordingly. Participants rationalized this response by drawing one of the resonance contributors of the base where a negative charge is present on the carbonyl oxygen (B). As one experienced GTA stated,

> *The most basic atom in this molecule is going to be one that might, at some point, carry a negative charge on it. So, by resonance, [oxygen B is] the only oxygen that can do that. […] Here, you usually think of these lone pairs as being pushed into the ring. So [oxygen A] has a net positive charge or delta positive at some point. So, it's also not very basic. And then kind of conversely, these electrons can be removed from the ring and delocalized to [oxygen B], so it has some negative charge on it. So, then it's the most basic.*

This GTA described their reasoning for choosing the most basic atom in the molecule shown above, which was similar to the processes observed from students in other research studies where students relied on resonance and charges to identify acids and bases.[43–46] Neither of the faculty members who reviewed our results were surprised that GTAs responded in this way and expected this response to be common among undergraduates as well.

The undergraduate student response chosen for this acid–base problem demonstrated similar reasoning as the ten GTA participants who chose oxygen B as the most basic site (Figure 2.3). This response was representative of students who prioritize resonance when considering the acidity or basicity of molecules. The undergraduate student demonstrated their knowledge of resonance and used resonance as a rationalization for oxygen B being the most basic. They correctly chose the phenol proton as the most acidic proton and drew the corresponding products. Participants discussed different reasons why a student would respond this way, which demonstrated their TS-PCK for this problem.

**Learner's prior knowledge.** When considering the prior knowledge this student might hold, nine GTA participants (four of ten incoming GTAs and five of seven experienced GTAs) noted that this student likely understands resonance, understands that one of the resonance contributors leads to oxygen B holding a negative charge, and this negative charge implies that oxygen B is basic. Two of three faculty participants echoed this sentiment. One incoming GTA stated:

> *I guess what the student here was thinking that if you take the electrons from the oxygen furthest away from the carbonyl, you could resonate it through the system, and you would be able to have a negatively charged oxygen that wants to be protonated and go, and then that nucleophilic [oxygen B] would be able to go and attack the hydrogen and remove it from the phenol.*

As this and other participants note, the undergraduate student used their knowledge of resonance to complete the proton transfer between the two given molecules. While it is unclear whether the undergraduate student considered other effects (i.e., hybridization) when completing this mechanism, participants assumed that they did not. Using one parameter to reason through a mechanism has been seen in other research, and often leads to limited and incorrect problem solving in students.[25]

**What makes the topic difficult.** When considering what makes this problem difficult, eleven GTA participants (eight incoming GTAs and three experienced GTAs), along with two faculty participants, voiced that the most difficult part is simply identifying the most basic site, especially because the student needs to consider various effects on basicity, like resonance, hybridization, induction, etc., as demonstrated by an experienced GTA:

> *I think the difficulty in this question comes from remembering how to balance the difference between the effects of hybridization and localized versus delocalized electrons, and then kind of where thinking about partial charges could fit into all of that. […] They were more concerned with showing the partial negative charge on the oxygen, or at least that you could have a partial negative here to make it more basic, over considering hybridization of this oxygen here.*

Again, participants identified one of the major difficulties of proposing mechanisms: considering many contributing variables.[25,27]

In addition to balancing effects on basicity, seven GTA participants (four incoming GTAs and three experienced GTAs) and all three faculty participants noted that the question statement made this problem difficult. Namely, the part of the question that prompted students to consider resonance may have misled students. An incoming GTA stated, “Definitely I think what makes this response difficult is, ‘Show the best resonance contributor when more than one is possible.’” Participants recognized that this was misleading to students, as it encouraged considering resonance when completing a mechanism in which considering resonance leads to the incorrect products. One of the faculty members who reviewed our results noted that the problem statement likely had the strongest influence on the student's response, and “is more to blame than anything else.”

**Curricular saliency.** Compounding this difficulty is the structure of introductory organic chemistry courses. Five GTA participants (three incoming GTAs and two experienced GTAs) and one faculty participant demonstrated evidence of curricular saliency during this part of the interview, possibly due to our interview protocol. For those who did demonstrate curricular saliency, they noted that resonance is a key topic in this course. In lecture, students are shown many examples where resonance plays a key role in the reactivity of a molecule, which could have influenced this student’s response. An experienced GTA explained, “especially in [organic chemistry I] how much time they spend learning about resonance, that any time in a problem like this that it's mentioned they hone in on it because they learn it so often.” As this GTA stated, students are almost trained to primarily consider resonance in this course, which likely influenced their response to this question.

**Representations.** For this question, participants did not demonstrate knowledge of representations. This finding is likely due to the nature of this question—the representations of the molecules above did not influence the student’s response in the same way that the representations of molecules in the substitution reaction question did.

**Teaching strategies.** While the teaching strategies mentioned by participants varied, one teaching strategy was utilized by four participants (two experienced GTAs and two faculty): to refer the student to the pKa table and to use that to explain why the mechanism proceeds the way it does. One faculty participant described this below:

> *I would say look on your pKa table. And so, what you can see is, yes, for sure an oxygen, an sp$^3$ hybridized oxygen atom with lone pairs available definitely would be difficult to protonate. But it would be more difficult to protonate something that is a carbonyl oxygen, even an ester.*

Two experienced graduate students also mentioned the same teaching strategy, but with less confidence:

> *I would definitely first review my own knowledge and make sure that I could explain it first. […] Once I really gathered a strong explanation, I would try to explain to them in terms of always using their pKa table, especially when they are given more than one option.*

> *Hopefully, they recognized that it probably could have been any of these lone pairs to reach out, and then if they weren't able to identify that, at least it would be an oxygen lone pair. Talk to them about how to read their pKa table about that*.

In this quote from an experienced GTA—one of the eleven participants that initially responded incorrectly and chose the carbonyl oxygen (B) as the most basic oxygen—they explained that they would first review the content to make sure they understood it themselves before using the pKa table to explain the mechanism to a student. This experienced GTA demonstrated that content knowledge is a prerequisite for developing PCK, aligning with findings from prior studies.[14,30,35,37] This finding is emphasized even further in the cases where graduate students answered the question incorrectly and then did not provide a teaching strategy.

Through further inductive analysis, we identified that eight participants (six incoming GTAs and two experienced GTAs) did not provide a teaching strategy for the acid–base reaction question (Figure 2.4). This number is likely much higher than for the substitution reaction question, where only two participants did not provide a teaching strategy, because this problem proved to be much more challenging. When asked how they would help this student, participants responded with, "hopefully, I'd be prepared and explain why that oxygen is not the one that attacks," or "I

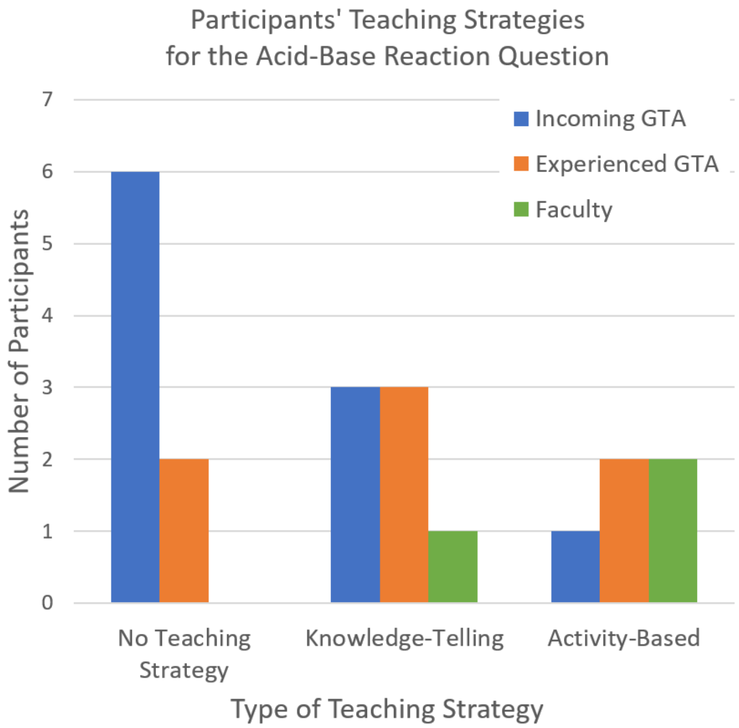


**Figure 2.4.** Participants' teaching strategies for the acid-base reaction question.

honestly probably would have said that it's correct, unfortunately.” Six GTA participants (three incoming GTAs, three experienced GTAs) provided a knowledge-telling teaching strategy. For example, an experienced GTA stated, “I would have told them that the $sp^3$ oxygen is probably more basic because it is less electronegative, so it’s more likely to pull off that hydrogen.” Three GTA participants (one incoming GTA and two experienced GTAs) provided a teaching strategy that involved some sort of activity to help this student. One experienced GTA, for example, noted that they “would ask them to draw both resonance structures—or all the resonance structures for this, and […] based on that, give me some reasons as like, is there aromaticity effect?” Figure 2.4 demonstrates the distribution of each teaching strategy type across our participant groups.

As demonstrated in Figure 2.4, incoming graduate students tend toward the left portion of the graph, with over half of the incoming GTAs not providing a teaching strategy, one third providing a knowledge-telling teaching strategy, and one providing a teaching strategy involving an activity. Faculty members tend toward the right portion of the graph, with two providing a teaching strategy involving an activity, and one providing a knowledge-telling teaching strategy. Experienced GTAs are distributed over all three categories of the graph.

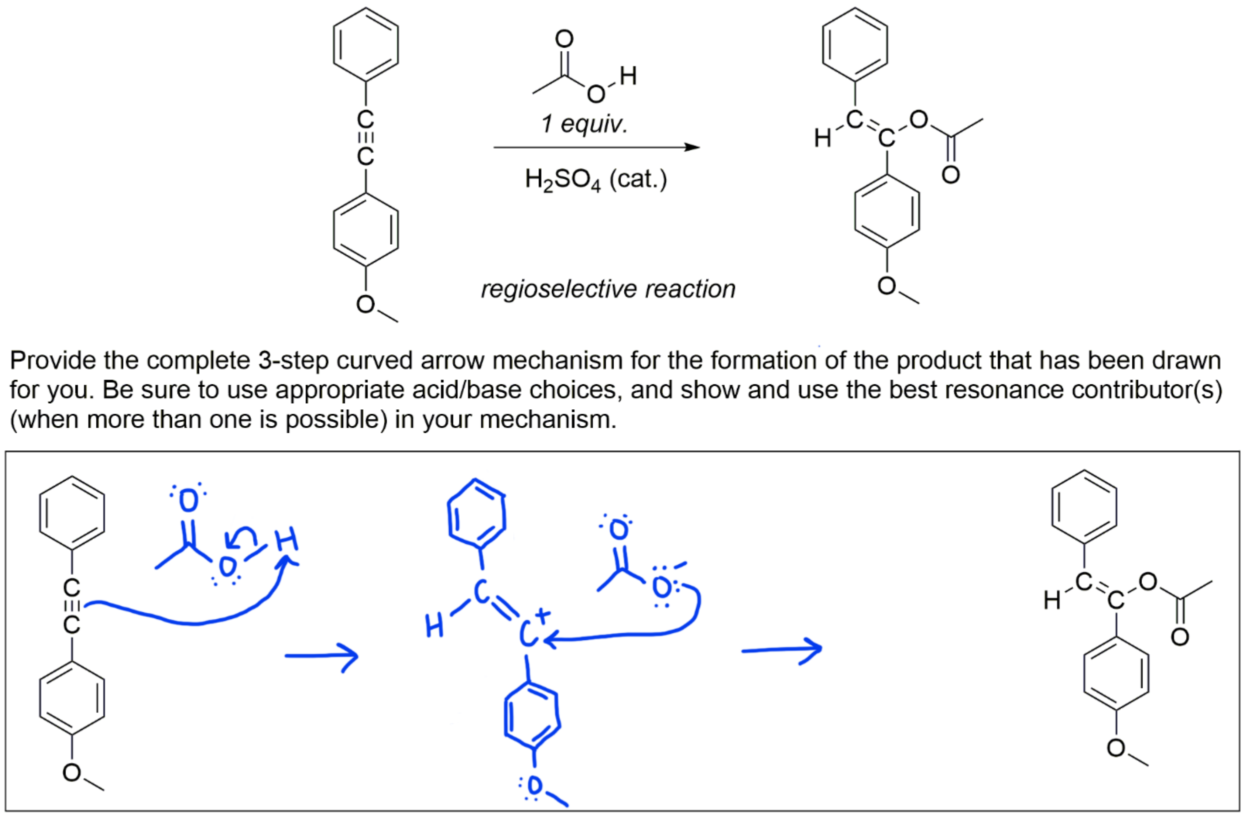
### 2.9.3 Question 3: Addition reaction

The third exam question was focused on an acid-catalyzed addition reaction (see Figure 2.5). Students were given the structures of the starting material, reagent, and product, and the catalyst was given as a molecular formula. Students were asked to provide the curved arrow mechanism for the transformation and were prompted to use appropriate acid/base choices, to show and use the best resonance contributor, and to draw a three-step mechanism. The answer key is provided in the supporting information, Figure 2.9.

Overall, there was variety in the ways participants completed this mechanism. For example, in the first step of the mechanism in which a proton is added to the triple bond, four participants first showed the protonation of acetic acid at the carbonyl oxygen. They used this protonated acetic acid in the first step of the mechanism as the proton source. Two participants protonated acetic acid at the $sp^3$ oxygen and used this protonated acetic acid in the first step of the mechanism as the proton source. Four participants used sulfuric acid in the first step of the mechanism, and two participants used a generic proton. Four participants used neutral acetic acid, and one participant did not respond at all.

The rest of the mechanism varied as well. The faculty members that reviewed our results were unsurprised by the variety in GTAs' responses to this mechanism question. They noted that across undergraduate institutions, there is a variety in how the source of protons are taught, and in some cases, the proton source is unspecified. This sometimes occurs even at a single institution; when completing this mechanism, one faculty member gave an "Organic Chemistry I" answer and an "Organic Chemistry II" answer, where the structure of protonated acetic acid varied. Faculty participants noted that identifying how the catalyst is used is the most difficult part of this mechanism. Overall, more concepts need to be considered when completing this mechanism than in the previous two mechanisms.

In the undergraduate student response to this problem (Figure 2.5), the student did not incorporate the sulfuric acid catalyst (pKa = −9) into their mechanism, but rather protonated the alkyne starting material with acetic acid (pKa = 4.8). Again, this is consistent with the findings of Kozma and Russell[20] and others that have shown that students struggle to interpret different representations and often focus on surface-level features. In this particular problem, all molecules



Provide the complete 3-step curved arrow mechanism for the formation of the product that has been drawn for you. Be sure to use appropriate acid/base choices, and show and use the best resonance contributor(s) (when more than one is possible) in your mechanism.

**Figure 2.5.** Undergraduate student response to the addition reaction question.

are represented in their structural form, except for the sulfuric acid catalyst. It follows that this student may not have recognized the role of sulfuric acid because surface-level features are not as evident in the molecular formula representation.[59] It is also important to consider Bhattacharyya and Bodner's[5] research in which students' primary focus when completing a mechanism was to draw curved arrows that provided the correct product without always considering the feasibility of the chemical transformations. We see the same sort of method in Figure 2.5, where the student drew curved arrows that lead to the product but did not consider the acidic conditions when drawing the curved arrows.

**Learner's prior knowledge.** Similar to participants' content knowledge, participants' TS-PCK varied more for the addition reaction question than for the substitution or acid–base reaction questions. Participants offered a few different reasons to explain this student's response. Eight GTA participants (five of ten incoming GTAs and three of seven experienced GTAs) and two faculty participants noted that this student had some misunderstanding of the role of sulfuric acid in this mechanism, though the specific misunderstanding varied. For example, five incoming GTAs mentioned that the student did not consider the catalyst or that this reaction takes place in acidic conditions at all, and two experienced GTAs said that the student simply did not know how to use the catalyst. Two experienced GTAs and two faculty participants noted that this student forgot the threshold for which acids are strong enough to complete this reaction, implying that this student thought acetic acid was strong enough to complete this reaction itself. Something to note here is that one experienced GTA and one faculty participant said that acetic acid is, in fact, strong enough to complete the mechanism, and the sulfuric acid is not needed but should still be considered by the student.

Additionally, five GTA participants (four incoming GTAs and one experienced GTA), along with two faculty participants explained that this student mapped the starting material to the product and tried to complete the mechanism in the most simple way to get to the product. For example, one experienced GTA stated,

> *I think this is the most direct mechanism you could think of drawing. It's just not accurate with the pH you're in. They see they know they have to protonate [the starting material]. They have an acid (acetic acid). […] So they never involve $H_2SO_4$; maybe they thought it was just there to be confusing or something.*

This GTA noted that while this was the most direct mechanism that could be drawn, it did not consider the conditions in which the mechanism occurs. Similarly, an incoming GTA explained,

> *He strangely drew an anion. We can see we are under an acid situation. There should not be an anion because any anion if it occurs, will be neutralized by the proton in the system. It is not allowed, and I don't know where he came up with this idea. Maybe he just cannot think of any way to lead to the product, so he just made up his own reagent. And yeah, this happens when you can't think of anything, you just make up your own.*

This GTA assumed that the undergraduate student did not know how the product forms, so they made up their own path without making chemical sense. These sentiments reflect other studies in which students use the curved arrow formalism to "connect the dots" between the starting material and product without always making chemical sense.[5]

**Teaching strategies.** Once again, there was a large variety in the content of participants' ways in which they would guide this undergraduate student. Many teaching strategies focused on reviewing fundamental concepts of acid–base chemistry, like strong versus weak acids and pKa values. Other teaching strategies focused on important pieces of the question prompt: pointing out the number of steps, drawing resonance contributors, or simply pointing out the inclusion of the catalyst. We further categorized teaching strategies as a knowledge-telling teaching strategy or an activity-based teaching strategy. As shown in Figure 2.6, we see a similar pattern to the substitution and acid–base reaction questions, with most GTA participants provided a knowledge-telling teaching strategy (seven incoming GTAs and four experienced GTAs). For example, one experienced GTA said, "I would remind them that the active form of that acid is not this, and that this is your nucleophilic form, and that the nucleophilic oxygen is actually the one on the carbonyl, and explain to them that that's how the mechanism should have gone." A few GTA participants provided a teaching strategy with an activity (three incoming GTAs and three experienced GTAs). One experienced GTA said,

> *I would take them back to thinking about how fundamentally why we have this happening so that they realize that this needs to be protonated and then they can, I think their understanding of at least their pushing… if they understood that and I gave them that protonated molecule and I would ask them to do this again and with that protonated species and see if they can get there.*

One faculty member provided a knowledge-telling teaching strategy, and two provided an activity-based teaching strategy. One of the faculty members who provided an activity-based teaching strategy said,

> *I would probably start by reminding them about equilibria in acid–base reactions and have them try to draw it, like how much of the [deprotonated acetic acid] species would actually be present, to get them to take home the idea that you wouldn't have [deprotonated acetic acid] present in solution and you have lots of [acetic acid] but it's not the strongest acid, and you really need the strongest acid to do this. So, I'd probably review acid–base equilibria with them. Then I would ask them why they put the carbocation here. And if it was simply because of the product there, then I would remind them about resonance stabilization of cations. I'd probably simplify this example and give them a different one that was a little bit more straightforward to see if they understood what I just reviewed.*

This faculty member described how they would review the content that is relevant to completing this type of mechanism question, then ask the student to complete a simplified version of this mechanism before jumping back into this mechanism question.

Participants did not demonstrate consistent knowledge of what makes this topic difficult, knowledge of representations, or curricular saliency for the addition reaction question. We suspect this is due to the specialized knowledge that is needed to understand this mechanism, and because

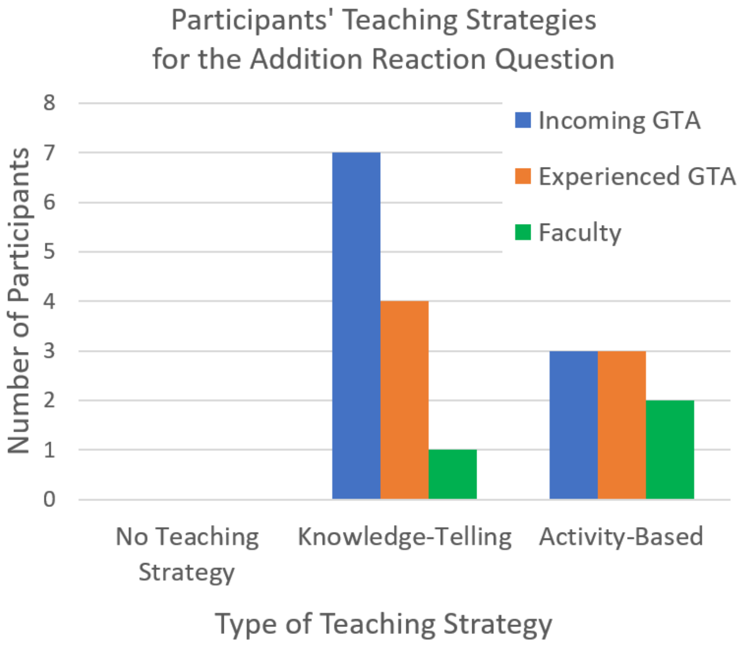


**Figure 2.6**. Participants' teaching strategies for the addition reaction question.

PCK is tied to content knowledge, how an instructor conceptualizes this mechanism will influence their knowledge for teaching this mechanism. While there is often consistency in the ways mechanisms are taught in one class at one institution, there can, in fact, be different probable ways in which a mechanism proceeds and thus nuanced differences across institutions and even across class levels at a single institution. GTAs come from different undergraduate institutions, which, as we have described, can influence their content knowledge for specific topics and their TS-PCK as a result.

## 2.10 Conclusions and implications

Given the difficulty in proposing and explaining mechanistic transformations in organic chemistry experienced by both undergraduate and graduate students, and that little is known about university instructors' knowledge for teaching this topic, we interviewed twenty university instructors of organic chemistry to gain insight into this knowledge. Participants thought aloud as they completed three mechanism questions chosen from introductory organic chemistry exams and assessed an authentic undergraduate student's response to each question. Through this interview, we elicited participants' TS-PCK for teaching organic chemistry mechanisms.

GTA participants' knowledge of what makes the problem difficult for the substitution and acid–base reaction questions was often consistent with literature on student understanding of organic chemistry—this was a strength in GTAs' TS-PCK. More specifically, GTAs noted that the representation of sodium chloride made the substitution question difficult,[20] and considering different effects on basicity to identify the most basic atom made the acid–base question difficult.[25,27] It is possible that GTAs can identify the difficulties of organic mechanism questions because they currently do or recently have struggled with the same aspects themselves. Strengths in this component of PCK can be leveraged to help develop other components of PCK in GTA training—like teaching strategies to support struggling students.[14,60]

Prior studies have indicated that graduate students struggle with introductory chemistry content.[5,27,29] In this study, we found that our GTA participants also exhibited weaknesses in their content knowledge of organic chemistry mechanisms, and we describe how this impacted their TS-PCK. In the substitution reaction question, the faculty participants noticed a limitation in the undergraduate student's understanding of the curved arrow formalism through an overcounting of electrons in the transition states. None of the GTAs noticed this mistake, and most GTAs assumed the undergraduate student completed the mechanism incorrectly because they thought sodium chloride was a covalent molecule. In an aforementioned study by Bhattacharyya and Bodner,[5] graduate students demonstrated a limited understanding of the curved arrow formalism. It is likely that our GTA participants also have a limited understanding of the curved arrow formalism. This weakness in content knowledge may have prevented our GTA participants from identifying the mistake in the student response (overcounting electrons in the transition states) that revealed a significant gap in the undergraduate student's knowledge. Identifying this mistake could in turn better influence GTAs' teaching strategies.

Moreover, in the acid–base reaction question, many GTA participants made the same mistake as the undergraduate student. They relied on resonance to identify the basic site of a molecule when hybridization needed to be considered as well. Additionally, almost half of our participants did not provide a teaching strategy to support the undergraduate student. Many were unable to provide a teaching strategy to help the undergraduate student achieve the correct answer because they did not understand the correct answer themselves.

Finally, in the addition reaction, there was such a variety in the way participants completed the mechanism that we detected few patterns in their TS-PCK. GTAs come from different undergraduate institutions where there may be nuanced differences in how complex mechanisms are discussed, which can be responsible for the variety in responses that we saw from our GTA participants. Accordingly, TS-PCK was limited and inconsistent for this mechanism. Aside from knowledge of learner's prior knowledge, we could not identify any facets of our participants' TS-PCK that was consistent across multiple participants.

To better understand these differences, research is needed to investigate how organic chemistry mechanisms are taught in various institutions and to identify how these methods of teaching are similar or different. Furthermore, it is important to investigate how practicing organic chemists reason through unknown mechanisms in their research. While we have many learning goals for students in organic chemistry courses, the goals should be informed by the ways mechanisms are used in practical situations.

The undergraduate student responses used in our interview protocol represented students with a limited understanding of the curved arrow mechanism and other symbols used in organic chemistry.[5,6,18] The undergraduate students' responses indicated that the student focused more on surface-level features than the underlying meaning of symbols,[20] which requires specific instruction to mediate.[3] Galloway et al.[9] and Webber and Flynn[8] demonstrated that in an organic chemistry course with a flipped course format and in which instructors precisely describe the use of the curved arrow mechanism, undergraduate students attributed meaning to the curved arrows when proposing both familiar and unfamiliar mechanisms. These findings indicate that when undergraduate students have opportunities to work through mechanisms with an instructor present to help guide them, they develop a conceptual understanding of the curved arrow mechanism.

The study presented here unveiled GTAs' limited knowledge of teaching strategies. Many GTA participants offered knowledge-telling teaching strategies, and some did not offer a teaching strategy at all. GTAs who demonstrated high levels of content knowledge in another study by Rollnick et al.[32] also offered limited teaching strategies by often just stating relevant content without considering students' prior knowledge. GTAs' deficiency in knowledge of teaching strategies is not entirely surprising since knowledge of conceptual teaching strategies is the most difficult component of PCK because it requires knowledge from the other components of PCK.[54] Without consistent responses, we cannot determine how GTAs might use their knowledge of learner's prior knowledge, representations, what makes the topic difficult, and curricular saliency to address students that these question responses represent—though GTAs are instructing students regularly in discussion and laboratory sections. Further research specifically investigating the knowledge of teaching strategies and the actual teaching strategies used in practice to address student difficulties with mechanisms is needed, as well as opportunities for GTAs to develop their knowledge of teaching strategies to best support students learning organic chemistry. One possible avenue to support GTAs' development of their PCK is through structured observations of high-quality GTA instruction with subsequent discussions of the observed instruction.[61] Mavhunga and Rollnick[35] and Rollnick[62] demonstrated that content knowledge also improves as instructors engage with TS-PCK interventions.

While we found that GTAs hold both content knowledge and TS-PCK of organic chemistry mechanisms, the assumption that graduate students begin graduate school with sufficient content knowledge to teach introductory organic chemistry courses should be carefully considered when designing training. GTA training should connect to the knowledge GTAs bring while also supporting the development of content knowledge and PCK they may be lacking.

## 2.11 Supporting information

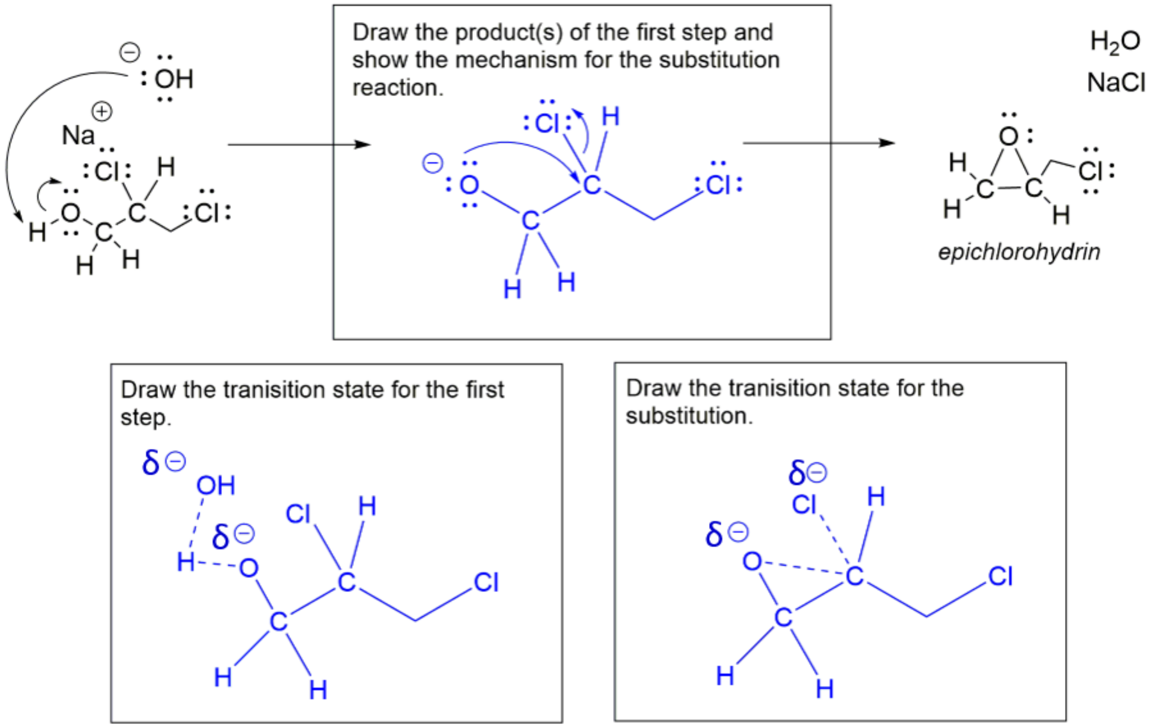
### 2.11.1 Our codebook

**Table 2.1**. Our codebook for analyzing interview responses.[35]

| Code | Definition | Example from the substitution reaction question |
|---|---|---|
| Learner's prior knowledge | Any mention of knowledge students have or do not have that is relevant to learning a new concept.<br>Assumptions of student knowledge, thinking, or problem-solving strategies.<br>Common alternative conceptions about content. | "I think the student probably doesn't know that it's going to be an ionic force what's going to be holding them together."<br>-incoming GTA |
| What makes the topic difficult | The ability to identify gate-keeping concepts within a concept that are difficult to understand. | "The most difficult part would be that the way they've [the instructors] drawn the sodium chloride could be somewhat misleading to people who don't have a proper understanding of ionic bonds versus covalent bonds, which is something that CHEM 210 students often struggle with at the beginning." -experienced GTA |
| Representations | Teachers' knowledge of a range of subject matter representations, including examples, illustrations, analogies, simulations, and models used to teach content.<br>Knowledge of limitations of representations and how they might influence students' reasoning. | One thing that I learned in teaching 210 is that the students constantly want to take their counterion and bind them to the molecule somehow. And so one thing that at least I tried to hit home to them was that if you see an ionic compound, keep it as an ionic compound and then you'll be able to better think about its ionic compoundness."<br>-experienced GTA |
| Curricular saliency | Teachers' knowledge of the learning of various topics relative to the curriculum as a whole.<br>Teachers' understanding of which topics are the most central and which are more peripheral.<br>Enables teachers to judge the depth to which a topic should be covered and hence the amount of time to spend on it. | "And maybe that's not reviewed a lot in my experience, always, in 210. So maybe by the time they got to the exam, they were not focused on that this would be an ionic bond." -incoming GTA |
| Teaching strategy | Any method of supporting students in correcting or improving their thinking. | "I would ask them, I think because the only thing I think is actually wrong on here is the covalent bond of the sodium chloride that they're drawing with their arrows, is I would ask them what type of bond that is, and they would probably tell me it's ionic. And I would then ask them, why don't we draw an arrow to that, then? Or just to the chlorine?"<br>-experienced GTA |

### 2.11.2 Answer keys to mechanism reaction questions

After a proton transfer, an intramolecular substitution reaction yields the "epichlorohydrin" product shown below, Complete this mechanism and draw the transition states.



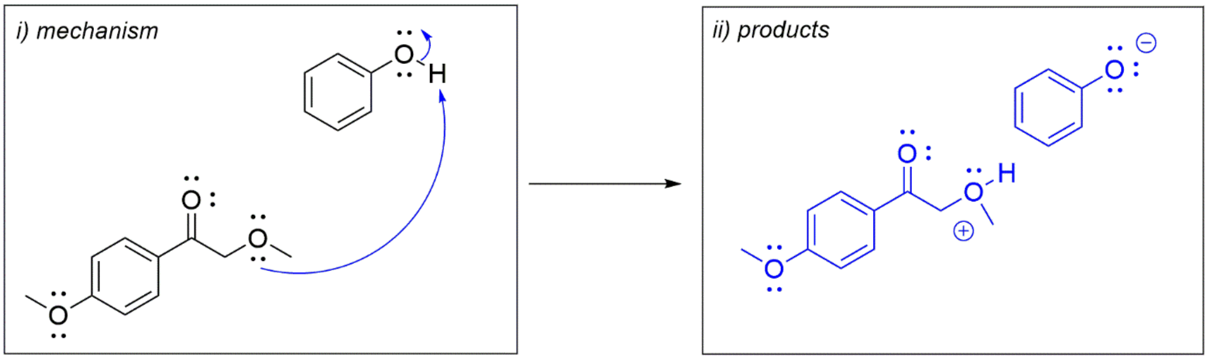
Draw the product(s) of the first step and show the mechanism for the substitution reaction.

Draw the tranisition state for the first step.

Draw the tranisition state for the substitution.

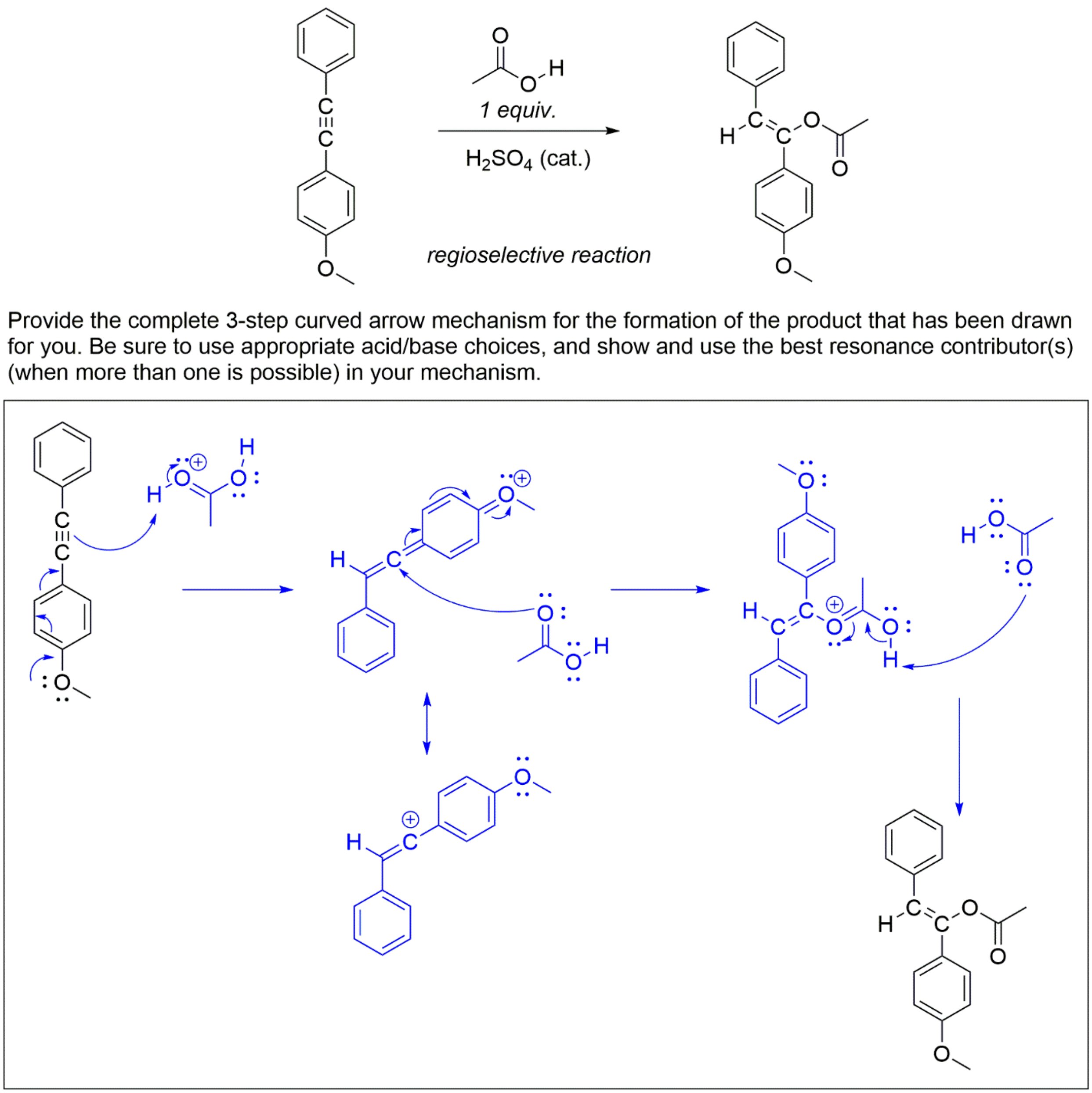
**Figure 2.7.** The answer key to the substitution reaction question.

Provide the curved arrow mechanism and product(s) for the following proton transfer reaction. Be sure to show the best resonance contributor when more than one is possible.



Student can still receive credit if other site is chosen.

**Figure 2.8.** The answer key to the acid-base reaction question. This task includes a question that is flawed, and we caution readers not to use it in an actual assessment.



Provide the complete 3-step curved arrow mechanism for the formation of the product that has been drawn for you. Be sure to use appropriate acid/base choices, and show and use the best resonance contributor(s) (when more than one is possible) in your mechanism.

**Figure 2.9.** The answer key for the addition reaction question.

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# Chapter 3

# Investigation of Chemistry Graduate Teaching Assistants' Teacher Knowledge and Teacher Identity

## 3.1 Initial remarks

The goal of this study was to investigate and describe GTAs' general teaching knowledge and their identities as teachers. This chapter constitutes the first of two studies for which the sociocultural theory of teacher learning was used as a lens to understand chemistry GTAs' experiences. The sociocultural theory of teacher learning provided a valuable perspective to understand how the context in which GTAs teach and their prior experiences in similar contexts influenced both their teacher knowledge and identity. Interviews were conducted with 22 graduate students employed as GTAs at various universities and had varying semesters of experience as a GTA. GTA participants taught various classes, including introductory (general chemistry and organic chemistry) discussions and lab, biochemistry discussions, computational chemistry labs, and more. Through qualitative analysis, the authors described GTAs' teaching knowledge and identity and major influencing factors.

Findings from this study include a description of chemistry GTAs' teacher knowledge, which included instructional goals, knowledge of students, classroom management strategies, teaching strategies, and assessments of students. The author also described the relationship between these teacher knowledge components. The teacher knowledge reported can serve as a foundation for leveraging such knowledge in GTA training. For example, GTAs know that students learn differently, and thus this knowledge can be leveraged to support GTAs in learning about various teaching methods that support students of all backgrounds and abilities. GTAs' teacher knowledge was largely influenced by GTAs' prior experiences as students and notably was not influenced by GTA peers or graduate school mentors. This may be due to a lack of social interactions centered around teaching in the GTA context.

Our GTA participants reported feeling unprepared to teach, but they hoped to gain a better understanding of course material and experience as a teacher through their GTA role. GTAs wanted students to perceive them as being an informal, approachable resource. Our participants often identified as lab managers or tutors, which inhibited their motivation to develop their teaching skills. This potentially relates to the central challenge with GTA teaching and learning that has been identified across the STEM education community: GTAs need to lead discussion and lab sessions to teach undergraduate students well, but STEM departments typically do not provide the training, support, recognition, or encouragement necessary to encourage GTAs to develop their identities as teachers and thus fulfill this role.

A prolonged collaborative space, such as extended trainings or other professional development programs, may help foster social interactions within chemistry departments that may positively impact GTAs' identity and knowledge. This space should provide GTAs opportunities to discuss their challenges and reflect on their experiences. Furthermore, these spaces should build upon the prior knowledge of teaching and learning that GTAs bring with them to graduate school while supporting GTAs in aligning their teaching goals, teaching strategies, and student assessments.

This chapter first appeared as a research article in the *Journal of Research in Science Teaching*, and the original publication and copyright information are provided below. The original publication was modified to adhere to Rackham dissertation formatting requirements, though no additional changes were made. Dr. Alena Moon assisted with study design, parts of data collection, qualitative data analysis, and writing portions of the published article. Dr. Nicholas Potter assisted with data collection. All remaining work, including remaining data collection, qualitative data analysis, and manuscript writing were completed independently by the author.

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## 3.2 Abstract

Graduate students play an integral role in undergraduate chemistry education at doctoral granting institutions where they routinely serve as instructors of laboratories and supplementary discussion sessions. Simultaneously, graduate teaching assistants (GTAs) balance major research and academic responsibilities. Although GTAs have substantial instructional facetime with large numbers of undergraduate students, little is known about their conceptions of teaching or their identities as teachers. To investigate the knowledge that GTAs have regarding teaching in this unique context, their teaching identities, and how these developed, we conducted 22 interviews with graduate students from several universities at various levels in their graduate school career using a modified Teacher Beliefs Interview. Interviews were analyzed for two overarching teacher learning constructs: teacher knowledge and teacher identity. We characterized chemistry GTAs' teacher knowledge and identity and determined major influencing factors. We found that chemistry GTAs often identified as a tutor or lab manager, which hindered their self-investment in developing as teachers. The results presented herein contribute to an understanding of GTAs' teacher knowledge, teacher identity, and their teaching context, from which training can be designed to best support GTA development.

## 3.3 Introduction and background

### 3.3.1 Graduate teaching assistants in undergraduate STEM education

Thousands of undergraduate students at doctoral-granting institutions are instructed by graduate students who are also managing their own course and research responsibilities. STEM graduate teaching assistants' (GTAs') teaching assignments typically range from 10 to 20 hr each week, during which GTAs are expected to be instructing undergraduate students in a laboratory or discussion setting, preparing to teach assigned sections, grading student work, and hosting office hours. Laboratory and discussion sections are typically composed of 20 to 30 students, and consequently, GTAs have more facetime with undergraduate students than professors who teach large enrollment lectures.[1] During laboratory sections lead by GTAs, undergraduate students gain fundamental hands-on experience in performing experiments and analyses, and during discussion sections, course content is reinforced or learned for the first time. Given their central role in undergraduate STEM education and because they are uniquely different from post-secondary instructors and pre-service teachers, the design, implementation, and assessment of GTA training programs are emerging foci in STEM education literature.[2,3]

GTAs comprise a unique population because, while they are essential contributors to undergraduate education, they work in an environment that places more focus on research than teaching[4–6] and where teaching is sometimes solely viewed as a means of financial support.[7] Moreover, GTAs rarely have formal teaching experience and therefore rely heavily on their content knowledge to teach,[7] though it is well known that content knowledge alone is not sufficient for effective teaching,[8,9] and in some cases, GTAs do not have adequate content knowledge required to teach introductory courses.[10] One in every three STEM GTAs will go on to become a faculty member or instructor within 6 years of receiving their PhD.[11] Teaching as a GTA commonly has a large influence on faculty members' and instructors' conceptions of teaching and learning as this experience is oftentimes their first introduction to formal teaching.[12] GTA training currently takes on many different forms—weekly staff meetings throughout the semester, one-day or one-week workshops before the start of fall semester, or half- or full-semester pedagogy courses—depending on the university. In some cases, training is not provided at all.[13–17]

Investigations into how GTAs experience and conceptualize their role as instructors have shown that GTAs teach using instructive (teacher-centered) teaching practices and conceptualize their role as transferring information to students,[4,18,19] neither of which align with the current national call for the implementation of evidence-based teaching practices.[20] Kurdziel et al.[18] conducted a study in which inquiry-based general chemistry laboratory GTAs were interviewed and observed. The authors found that GTAs did not have the instructional skills needed to facilitate inquiry and that GTAs had ill-informed conceptions about how students learn. GTAs in this study thought that students learn best when information is clearly and cleanly presented to them.[18] This result, along with findings from other studies that demonstrated GTAs are not prepared for their instructor role, are quite problematic for undergraduate STEM education.[4,18,19]

With a national call to implement reformed-based practices in undergraduate STEM courses and to understand the research culture of doctoral programs,[20] recent studies have focused on developing and evaluating training sessions to support GTAs across STEM disciplines, especially because 70% of life and physical science classes are taught by GTAs.[2,21–23] Few studies focused specifically on chemistry GTAs.[6,16,24] Despite this work thus far, a call to improve GTA training and instruction remains.[25–27] The purpose of this study was two-fold: to investigate how chemistry GTAs conceptualize teaching and their instructional role to (a) further inform the design of GTA training to specifically address the needs of GTAs and (b) to contribute to an understanding of chemistry GTAs' teacher knowledge and teacher identity.

### 3.3.2 Teacher beliefs and practices

Teacher behavior and actions in the classroom are influenced by teachers' knowledge and beliefs about teaching and learning.[28–31] as well as their teacher identities.[32] Teacher knowledge and teacher beliefs are viewed as independent but strongly interconnected—beliefs refer to personal values, attitudes, and ideologies, and knowledge refers to ideas derived through formal education and experience.[33,34] Gibbons et al.[28] conducted a large-scale survey study focused on the self-efficacy of chemistry faculty members, teacher beliefs about how teaching and learning should occur, and self-reported instructional practices. The results from this study demonstrated that chemistry faculty's teaching beliefs aligned with their practices, reinforcing the connection between teacher beliefs and instruction. The authors of this study recommended to begin teacher reform with a focus on teacher beliefs,[28] which is lacking in chemistry GTA training designs.

Furthermore, it has been shown that professional development programs that do not consider teachers' attitudes and beliefs have been ineffective.[35,36] Alignment of teacher beliefs and teacher practices are a focus in pre-service teacher education programs. K-12 teacher training works to surface, challenge, and develop pre-service teacher beliefs as a foundation for developing teaching practices. Similarly, effective and efficient GTA training must elicit and be informed by GTA teacher beliefs,[37,38] which have been investigated in other STEM disciplines[2,39,40] but, to our knowledge, have not been investigated for chemistry GTAs.

Luft and Roehrig[41] designed a semi-structured interview protocol, the Teacher Beliefs Interview, to investigate teacher beliefs. The Teacher Beliefs Interview was first utilized to explore and capture the teacher beliefs of secondary science teachers. Luft and Roehrig[41] uncovered a range of beliefs, from traditional and teacher-focused to reformed and student-focused, within and across participants. The Teacher Beliefs Interview has been used in a variety of contexts, including studies of GTA teacher beliefs in geoscience and biology.[2,39] Investigations of teacher beliefs are motivated by the potential to gain insight into the knowledge teachers have about teaching and learning, which correspond to the instructional practices used to instruct students.[28,42]

The primary goal of implementing training and professional development programs is for teachers to gain knowledge of teaching and learning. Reflection has been shown to be an essential component in learning how to teach science[43,44] Wenger[45] states that there is a reciprocal relationship between teacher identity—how a teacher views themselves and identifies as an educator—and teacher knowledge, and that reflecting on one's experience in teaching promotes the growth of this relationship. For example, in a study focused on new primary and secondary science teachers' identities, one participant valued the messiness of science and strove to provide students space to learn through their mistakes. However, she was hesitant and discouraged from allowing her students to engage in messy science, because she viewed part of her role as a science teacher as someone who encourages the correct answer.[46] It is therefore important to consider teacher identity alongside teacher knowledge as they influence one another. Sandi-Urena and Gatlin[47] investigated factors that contribute to chemistry GTA identity and found that prior experiences, training, epistemological beliefs, beliefs about the nature of laboratory work, and involvement in the laboratory setting contribute to the construction of GTA identity. In another study, Lane et al.[48] demonstrated how interest in teaching, professional development, teaching experiences, mentors, and recognition as a teacher influence GTA teaching identity within the research-focused culture of doctoral granting institutions. Other studies have suggested that departmental culture may impact GTAs' conceptions of teaching and conceptions of their role as an instructor.[4] GTA teacher knowledge and teaching identity have been investigated separately, but the relationship between chemistry GTAs' teacher knowledge and teacher identity remains unexplored. In our study, we contribute to an understanding of this relationship by investigating the teacher knowledge and teacher identity of chemistry GTAs at various levels in their graduate school careers.

### 3.3.3 Theoretical framework

In the sociocultural theory of teacher learning perspective, knowledge is shared across all entities of a community (people and artifacts) and therefore, an individual learning to teach must interact with the entities through participation in their teacher role. This theory appropriately frames our study given that it specifically places teachers within their social, physical, historical, and cultural contexts.[49,50] Entities are often unique to their respective communities, and consequently, teacher expertise is linked to the circumstances to which it pertains.[51,52] In other words, given the social, physical, historical, and cultural differences between universities and primary or secondary school settings, GTAs will learn about teaching in a different way than, for example, in-service teachers. Furthermore, what is expected of an "expert GTA" may differ from what is expected of an expert in-service teacher. GTAs learn from experience through interacting with entities with which they teach: GTA peers, professors, research mentors, undergraduate students, and all tools and resources—books, worksheets, exams, lab equipment, and so on. While research on pre- and in-service science teacher learning can inform research on GTAs, the unique culture of doctoral granting institutions and the GTA role warrants investigations focused on this distinct population.

In the study presented herein, we have analyzed teacher learning through a lens described by Wenger[45] and further developed by Kelly.[51] Kelly took a sociocultural perspective and expanded upon Wenger's four central components of social theory of learning: (a) teacher knowledge, (b) teacher identity, (c) teacher knowing, and (d) teaching practices. We focus specifically on (a) teacher knowledge and (b) teacher identity in this present study. Teacher knowledge refers to teachers' knowledge base for teaching and student learning; it encompasses pedagogical knowledge, pedagogical content knowledge, and subject matter knowledge. Teacher knowledge is derived from formal education and experience in instructional settings—either as a teacher or a student. Teacher knowledge is often unique to teachers' individual contexts, so it involves more than applying a well-developed body of knowledge. A key aspect of the sociocultural view of teacher knowledge is that teachers continuously develop their teacher knowledge as they engage in their teaching practice, and furthermore, expertise is described as "the constant and iterative engagement in constructing and reconstructing professional knowledge" (p. 509).[51] GTAs may draw upon their experiences as students or instructors and from GTA training to inform their initial teaching. As GTAs continue to teach and interact with the entities of their community, their teacher knowledge develops based on these experiences.

The second component, teacher identity, refers to teachers' perceptions of their role and their personal goals and desires. Teacher identity is influenced by teachers' contexts, and specific contexts may favor the construction of certain identities. Kelly[51] described the social process of developing a teacher identity:

> Teachers' identities are neither located entirely with the individual nor entirely a product of others and the social setting. They can be regarded as the ways in which practitioners

> see themselves in response to the actions of others toward them; that is they are the constantly changing outcomes of the iteration between how practitioners are constructed by others, and how they construct themselves, in and away from social situations (p. 513).

Teacher identity is a social construct—it is a product of how teachers view themselves and how they are viewed by others. Teachers construct their identity by interpreting experiences with others in their community and develop their identities over time as they continue to take on instructor roles and develop more autonomy in their practice.[53] GTAs may initially interpret the meaning of their role through interactions with administrators, professors, or peers. As GTAs progress throughout their graduate school careers and continue to interact with members of their community, their identities may shift in varying ways. Understanding the intricacies of teachers' identities provides insight into the motivations behind how teachers think and act,[32] and thus is an important window into understanding teacher knowledge.

The third component, teacher knowing, refers to teachers' implementation and adjustment of their knowledge base for teaching and learning. Teacher knowledge, the students present, the working practices of the school, the resources available, and previously internalized experiences can all contribute to the actions teachers take within their classroom, and the outcomes of these actions can influence future courses of action. For example, a GTA who is used to lecture-style classrooms might initially lead their discussion section with a lecture, but if the GTA notices students are not responding well, they might use a different teaching technique.

Lastly, teaching practices refers to teachers' engagement in the discourse, norms, and working practices of teaching both inside and outside of the classroom (e.g., assigning homework, implementing whole-group discussions, collaborating with other teachers, or sharing lecture notes). Expert teaching practices are unique to teachers' contexts as specific schools may encourage certain practices over others.[51] For example, sharing lecture notes is a common practice in post-secondary schools. In this study, we investigate the teacher knowledge and teacher identities of chemistry GTAs to gain insight into what and how GTAs learn about teaching within their specific contexts.

### 3.4 Research questions

Given the prominent call for improving STEM GTA training and the lack of insight into chemistry GTAs' conceptions of teaching from which training should be developed, the goal of this project is to investigate how chemistry GTAs conceptualize teaching and their instructional role and to contribute to an understanding of chemistry GTAs' teacher knowledge and teacher identity. Our guiding research questions are informed by the sociocultural theory of teacher learning proposed by Kelly:[51]

> What is the nature of chemistry GTA teacher knowledge and teacher identity?
> What factors influence the development of chemistry GTA teacher knowledge and teacher identity?

### 3.5 Methods

The objective of this study was to qualitatively investigate the beliefs for teaching held by chemistry graduate students to better understand their teacher knowledge and teacher identity. Specifically, we aimed to identify the nature of chemistry GTAs' teacher knowledge and teacher identity and to explore factors that have influenced the development of these constructs. The findings of the study presented herein are grounded in (a) the experiences of the chemistry graduate students and (b) our conceptual framework and can serve as the basis for empirical work aimed at testing hypotheses about the interconnected relationships between graduate student beliefs, knowledge, and identities.

#### 3.5.1 Participants and setting

We interviewed 22 chemistry doctoral students with a range of teaching experience from four research institutions. A purposeful selection process[54] was used to recruit participants with experience ranging from zero to five or more terms of teaching as a GTA. First, a subset of 15 participants were recruited and interviewed from a single Midwestern institution. Few of these participants had substantial teaching experience, and after initial analysis, it was determined that saturation was not reached. An additional seven participants with more experience were then recruited from this and three other institutions. All participants entered research-focused chemistry doctoral programs in which graduate students are primarily evaluated based on their capabilities to conduct research. In these programs, funding is provided to graduate students through teaching assistantship, research assistantship, or fellowship programs. GTAs are frequently hired to teach laboratory or supplementary discussion sections for large-enrollment courses where many GTAs are teaching the same course. The GTA training programs for 20 of our participants were structured as a short one- or two-day workshop before their first fall semester, one participant underwent a

5-day training, and one participant underwent an eight-week GTA training pedagogy course. Some faculty instructors may hold course-specific weekly staff meetings to keep GTAs on track and informed. Nine participants identified as female, one participant was an international student, 21 participants went to graduate school in the Midwestern United Sates, and one participant went to graduate school in the Western United States. All participants were recruited via email and consented to participate using an IRB reviewed consent process. IRB approval was obtained for this study and all participants were given pseudonyms to maintain confidentiality. Participant information is included in Table 3.1.

**Table 3.1.** Participant semesters as a GTA, type of class taught as a GTA, length of training, and undergraduate institution. [a]International student. [b]Western US graduate school.

| Participant | Semesters as a GTA | Type of class taught | Length of training | Undergraduate Institution |
|---|---|---|---|---|
| Abby | 1 | Discussion | 1-2 days | R1 |
| Vanessa | 1 | Discussion | 1-2 days | R1 |
| Bud | 1 | Discussion | 1-2 days | R2 |
| Calvin[a] | 1 | Discussion | 1-2 days | R2 |
| Mallory | 1 | Discussion | 1-2 days | PUI |
| Jamie | 1 | Lab | 1-2 days | R1 |
| Erica | 1 | Lab | 1-2 days | PUI |
| Robert | 1 | Lab | 1-2 days | R2 |
| Faith | 2 | Discussion | 1-2 days | PUI |
| Frankie | 2 | Lab | 1-2 days | R1 |
| Phil | 2 | Lab | 1-2 days | PUI |
| Allison | 3 | Discussion | 1-2 days | PUI |
| Sol | 3 | Discussion | 1-2 days | R2 |
| Grace | 4 | Discussion + Lab | 1-2 days | R1 |
| Andrew | 5+ | Lab | 1-2 days | PUI |
| Amanda | 5+ | Discussion + Lab | 1-2 days | R1 |
| Brian | 5+ | Discussion + Lab | 1-2 days | PUI |
| Eman | 5+ | Discussion + Lab | 1-2 days | PUI |
| Janice | 5+ | Discussion + Lab | 1-2 days | R1 |
| Jacob[b] | 5+ | Discussion + Lab | 1-2 days | PUI |
| Macklin | 5+ | Discussion + Lab | 5 days | PUI |
| Daphne | 5+ | Discussion + Lab | 8 weeks | PUI |

### 3.5.2 Data collection

A semi-structured interview protocol was used to capture chemistry GTAs' teacher beliefs, previous experiences as a student and as a teacher, and beliefs about the nature of science (see Supporting Information).[55] The interview protocol followed closely to the Teacher Beliefs Interview.[41] Questions were added to provide GTAs with opportunities to discuss factors—undergraduate experiences, any experiences teaching, and beliefs about the nature of science—that may have contributed to the development of their teacher beliefs.[47] Multiple researchers conducted thirteen interviews in 2016, four interviews in 2017, and five interviews in 2018. Interviews ranged in length from 45 to 90 min and were conducted in person, via Skype, or via Google Hangouts. There were no noticeable differences in the interviews conducted by different media or at different time points. All interviews were audio recorded and transcribed verbatim.

### 3.5.3 Data analysis

We approached our data analysis with theoretical perspectives of sociocultural theory of teacher learning. All interviews were coded through provisional coding methods,[56] during which data was coded using predetermined codes derived from our theoretical framework. The application of the conceptual framework to these data was reviewed by two experts; one with expertise in teacher knowledge research and the other an experienced college level chemistry instructor. During our first round of coding with predetermined codes, we coded for evidence of two of the four categories of teacher learning as defined by Kelly:[51] teacher knowledge and teacher identity. Because the other two categories of teacher learning, teacher knowing and teaching practices, are more active than reflective in nature, they cannot be fully captured in an interview and thus were excluded from analysis. During this round of coding, the authors noted that GTAs frequently referenced challenges they faced. Thus, challenges were added to our codebook. Interviewee responses could receive multiple codes if warranted. Responses that were coded for teacher knowledge or teacher identity were then open coded, and major themes were identified inductively from this round of coding (see Figure 3.1 and Table 3.2).

Interview transcripts were coded using the NVivo 11 Pro software. The first two authors coded a subset of interviews to ensure a common understanding of what counted as evidence of teacher knowledge and teacher identity and of each particular theme. Themes for teacher knowledge were: instructional goals, knowledge of students, classroom management, and teaching strategies. Themes for teacher identity were: role in the course, affect, personal goals, and desired student perception. Interrater reliability at the theme-level was calculated with the first author and another chemistry education researcher who was not involved in this study. The first author provided the other researcher with a codebook that included descriptions for each theme. The other researcher independently coded 10% of the data, and then met with the first author to discuss discrepancies and to elaborate on the descriptions in the codebook. The other researcher then independently coded an additional 10% of the data. Interrater reliability was calculated with this data set using the Fuzzy kappa statistic, which is a modified Cohen's kappa that allows for multiple codes to a single unit of analysis.[57] Our Interrater reliability value (0.86, Fuzzy kappa) indicated almost perfect consistency for the application of our coding scheme.[58] Given that GTAs comprise a unique population and thus their development of teacher knowledge and teaching identity will be distinct from other populations of instructors, this work extends and refines sociocultural theory to encompass this new population as we generated theories of GTA teacher learning.

GTA challenges and each theme for teacher knowledge and teacher identity were further investigated for subthemes—more specific features of the participants' challenges, knowledge, and identity. All features from each interview were individually summarized and listed in a Word document. The number of transcripts in which a specific feature appeared was recorded by pairing each feature with the corresponding participant pseudonym(s). If a feature appeared in five or more interviews, it was defined as a subtheme. Subthemes are summarized in Figure 3.1 and Table 3.2.

To examine the ways in which teacher knowledge themes may be connected or influence one another, we started by identifying excerpts coded for “teaching strategies” in each individual interview. Next, we identified any information within that interview that may have informed this teaching strategy for the given participant. All teaching strategy influences were noted and the number of times a certain influence played a role in informing teaching strategies across all GTAs was identified. If there was not a clear influence for a teaching strategy, that was noted as well. A similar process was followed to determine influential factors for other teacher knowledge themes.

Our next goal was to gain insight into how GTA training influenced GTA teacher knowledge. Responses to the interview question: *“How has this training influenced your teaching?”* (see Supporting Information) were investigated to determine which teacher knowledge themes were most commonly influenced by GTA training.

Finally, the relationship between challenges, teacher knowledge, and teacher identity was explored by focusing on instances where teacher identity codes overlapped with either challenges or teacher knowledge in each individual interview. For each of these instances, the given overlap between teacher knowledge and teacher identity themes was summarized and commonalities across GTAs were determined.

### 3.6 Transferability and trustworthiness

In the study presented herein, we took multiple measures to increase the trustworthiness and transferability of our results. We used purposeful maximal variation sampling—we interviewed GTAs from multiple universities and with different amounts of experience as a GTA—to increase the ability of the results discussed in this study to be transferrable to other settings.[54] We have written about our methods and results using thick, rich descriptions so that the similarities between our study and other contexts can be assessed.[59] Our comprehensive account of our study also lends itself to the trustworthiness of our conclusions, given that our interpretations and analysis are clearly described. Multiple researchers collected and analyzed the data, which requires extensive collaboration and consensus making and thus serves to mitigate the possibility of researcher bias. We considered rival explanations to ensure our explanations accurately encompass the experiences of our participants, and we received feedback from experts in science education research.

### 3.7 Limitations

Perhaps the most meaningful limitation emerged from the use of interviews, which prompted participants' reflections but provide no direct evidence of their teaching practices. Given results showing that teachers can overestimate the amount of reform in their teaching when self-reporting,[60] these results serve as a sort of upper bound of GTA's knowledge and identity. GTA teacher knowledge can be confirmed or better understood by conducting classroom observations. Additionally, we only capture one snapshot of GTAs' teacher identities through these interviews. GTA identity in practice should also be considered and could be investigated with observations. Only one of our participants was an international student, and their experiences learning to teach may be different due to unique barriers that international students face. Further research in this area is needed, as an average of 42% of chemistry doctoral students are international.[61] Finally, graduate student training is highly contextualized and varies within and across institutions and across national boundaries. The findings presented here were all collected at major research institutions in the U.S., the majority of them in the Midwest. These institutions happened to have comparable graduate training programs, but it is recognized that interview data collected at other institutions might paint a different picture of GTAs' conceptions and reported practices. A survey methodology would be a viable approach to eliciting and controlling for variations in GTA conceptions.

## 3.8 Results

### 3.8.1 RQ 1: What is the nature of GTA teacher knowledge and teacher identity?

#### 3.8.1.1 Teacher knowledge

While analyzing the interviews, five teacher knowledge themes were identified, which encompass chemistry GTAs' knowledge base for teaching and learning in the context of research institutions. The five themes were: *instructional goals, knowledge of students, classroom management, teaching strategies, and assessment of students.* Each theme is described in detail later, and Figure 3.1 includes a summary of all teacher knowledge themes and subthemes and the relationship between them.

The theme *instructional goals* refer to the goals that GTAs want to accomplish within their teaching section. Instructional goals ideally should inform all teaching practice by driving lesson plan and assessment design.[62] Five instructional goals were common across all GTAs: for their students to learn the course content, to answer their students' questions, to engage their students, to demonstrate the relevance of chemistry, and for their students to learn critical thinking skills. For example, Sol said, “I'm trying to accomplish that the students understand the material and are most prepared for the exam.” Some participant responses, like Robert stated in the following, focused more on answering students' questions:

> *Addressing their questions is really important, and that answering questions be a primary means of communication, as opposed to just me standing up doing a lecture, and then asking, ‘All right, any questions,’ in the last five minutes.*

Other GTAs were more focused on engaging students and may do so by connecting course content to examples or issues outside of the course. Phil described his goal of demonstrating the relevance of chemistry:

> *To say, you know, this isn't just something that we're teaching you because someone somewhere decided it was important. This is real life; people use it every day. […] So, to be able to make that connection to what are real chemists doing with the information you're getting in class. That, I think, is powerful for students hopefully. That's definitely what was powerful for me as a student*.

Most GTAs demonstrated having *knowledge of students*. It has been shown that instructors use knowledge of their students to guide their instructional decisions.[63] GTAs were most commonly aware that students are different, and some participants also noted that student learn differently. GTAs' knowledge of students—that students have different needs, interests, and goals—often influenced their instructional goals of demonstrating the relevance of chemistry to engage all students (Figure 3.1, Arrow D). Phil describes this in the following:

> *There's going to be a small set of students in there that actually want to be chemistry majors. […] For the ones who don't want to be chemistry majors, who want to do something else, I want them to have a better appreciation for chemistry, as being more than just a box they have to check on their way to medical school.*

The majority of our chemistry GTA participants were aware that students had interests and goals outside of chemistry (e.g., going to medical school). This motivated their instructional goal of demonstrating the relevance of chemistry to engage students in the course content.

The third theme, *classroom management*, refers to the methods GTAs have used to manage, facilitate, or structure their classroom. Classroom management skills are an essential part of teaching as they are used to create and maintain an environment in which learning can occur.[64] The two common methods GTAs reportedly employ to manage their classroom were directing students to office hours if they need more help and organizing students in groups. Bud described a situation where he responded to a student that was struggling to understand a concept:

> *I'd probably say a few more things and then move on anyway, because I felt like, if you're not getting it at the fifth one, probably I'd just say, "Come see me during office hours if this still isn't clear. We'll work through it, but we have to move on."*

Bud's quote was representative of participants who voiced utilizing office hours to deter spending class time working with an individual student. This management strategy may have been used to mitigate the challenge of managing time during relatively short discussion and lab sessions. However, in this case, managing time occurred at the expense of students' understanding. This reflection existed in contrast to the instructional goals of answering students' questions and for students to learn the content. It is possible, that due to the constraints of teaching short discussions and laboratories once per week with certain requirements set by the professors of the course, participants were unable to accomplish their instructional goals during discussion and laboratory section but used office hours as an additional time to work toward their goals of student learning.

GTAs had varying motivations for organizing their students in groups. Some GTAs organized their students in groups to make themselves more available as questions arose, some organized their students in groups because they preferred to interact with a few students at a time, and others reported organizing students in groups so students could help each other learn content (instructional goal), given the fact that students learn in different ways (knowledge of students). Eman demonstrated using groups to support learning as follows:

> *They can talk to each other about it, which also, I think helps their own learning because the more students talk to each other about chemistry, maybe they're not using the same exact wording or terminology that I'm using, so maybe they kind of hear it in a different way than from how I say it, and if you know, somebody thinks they feel comfortable enough about some topic to help another student with it, then that's probably a good evidence that they know what's going on in the classroom.*

Eman showed that her classroom management strategy of organizing students in groups was motivated by her knowledge of students—that students learn differently (Figure 3.1, Arrow C). Eman also demonstrated the belief that allowing students to work together would support their learning of the content (Figure 3.1, Arrow B).

*Teaching strategies* refer to the techniques GTAs have reported using to convey material to students and to facilitate students' learning. The most common methods that GTAs in this study used include not giving students direct answers to their questions, using basic concepts to explain more complex concepts, and connecting material to real life or other disciplines. Allison's quote was a representative report of using the teaching strategy of guiding students to the answer, “I usually like to answer questions with more questions, which is something that I hated when I was a student, but it turns out that it really works.”

Allison noted that she learned content when her instructors led her to the answer. Because she had this experience with a positive outcome (learning), she, along with many other participants, likely guided students to the answer as a way to accomplish the instructional goal of students learning content (Figure 3.1, Arrow A). Another way GTAs worked toward accomplishing student learning was through using more basic concepts to build students' understanding of more complex concepts. Vanessa described an example of when she scaffolded content for a student:

> *I've had one girl in office hours and she really really didn't understand why a carboxylate anion is negatively charged. So it's going back and just breaking that down to, okay so, just breaking it down and trying to put it in simpler and simpler terms. So, looking at oxygen on its own, and its valence electrons, and okay so now if we were to form bonds, now how does that affect the valence electrons in the shell of the atom?*

Vanessa noted that when her student was struggling with understanding the charge of a molecule, she guided the student though recalling properties of individual parts of the molecule (the valence electrons on one oxygen atom in the molecule), and used this basic understanding to build the students' understanding of the carboxylate anion. The final teaching strategy of connecting material to real life or other disciplines was closely tied to the instructional goal of demonstrating the relevance of chemistry—connecting course material to real life is a way to demonstrate the relevance of chemistry (Figure 3.1, Arrow E).

The final teacher knowledge theme, *assessment of students,* refers to the ways that GTAs determined if their teaching was effective or if students were learning. Four common methods of assessment were reported by GTAs in this study: examining their facial expressions, checking students' grades, asking rhetorical questions like, “do you understand?”, and determining if students could explain the concept themselves. For example, Erica demonstrated how she assessed student understanding by facial expressions by saying, “I think, I mean you can sometimes just see it in their eyes, like ‘yeah, I got it.’” Erica's quote was representative of participants who assess students' understanding using nonverbal communication. Other participants focused on grades as a form of assessment, and some, like Brian, required verbal communication:

> *Really, trying to explain it back, like, "okay, tell me what's going on here, explain what is happening." And if they could explain it back to me in a way that was correct and sounded like they understood it, that was really, you know, what I looked at.*

Notably, participants' assessment of students did not appear to be related to other teacher knowledge themes in our data.

Chemistry GTA teacher knowledge unveiled in this study creates an understanding of what types of knowledge GTAs have regarding teaching and learning. In addition to characterizing GTAs' teacher knowledge, we found that GTAs' knowledge of students influenced their instructional goals and their classroom management, and GTAs' instructional goals influenced their classroom management and teaching strategies. The characterization of and relationship between chemistry GTA teacher knowledge components are shown in Figure 3.1. With this understanding of chemistry GTA teacher knowledge, we are better able to design chemistry GTA training to build upon this knowledge and to support GTAs in maximizing their service to students.

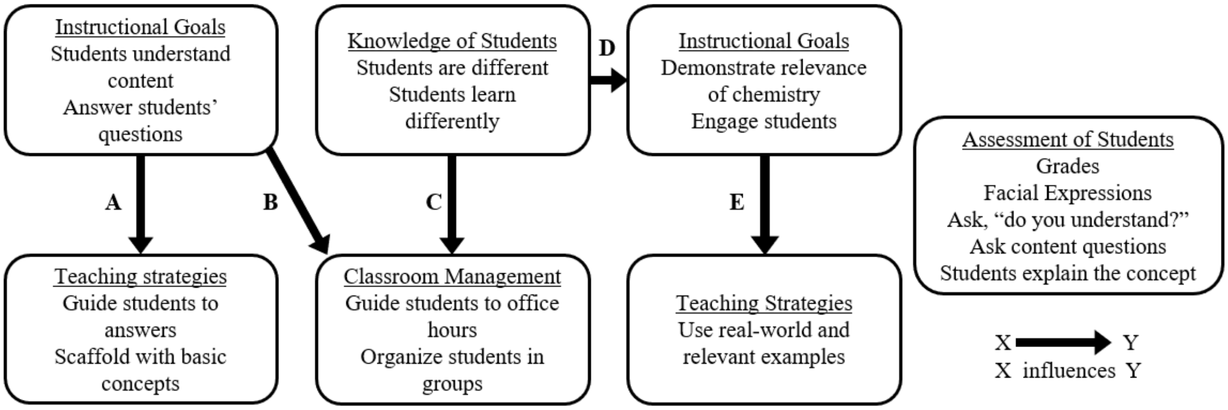

**Figure 3.1.** The characterization of and relationship between chemistry graduate teaching assistant (GTA) teacher knowledge components.

### 3.8.1.2 Teacher identity

Teacher identity is defined as the ways teachers view themselves and their roles as instructors and encompasses their personal goals and desires related to their teaching and professional development.[51] Teacher identity is a product of both how teachers view themselves and how they perceive to be viewed by others and is important to investigate as it influences teacher knowledge development.[51] Four themes regarding GTA teacher identity were identified: *role in the course, affect, personal goals, and desired student perception.* Teacher identity themes are described later, and Table 3.2 includes a summary of all teacher identity themes and subthemes.

*Role in the course* refers to the ways that participants viewed the purpose of their teaching role within the course they taught. This is a naturally social construct as GTA duties are defined and communicated by the chemistry department or course instructor for whom they teach. Participants in this study viewed their role as a link between students and the professor. They acknowledged that professors are more knowledgeable, but GTAs are more accessible.

Additionally, participants that have taught laboratory courses often viewed themselves as lab managers, as is consistent with another study focused on chemistry GTA identity.[47] Bud describes his view of his role in the course:

> *It's just a supplement to the main lecture. You should… whoever the professor is, is way smarter than me at this subject, hopefully, probably. You should focus on them and believe whatever they say, and then when you're confused, it's my job to try to help you not be as confused and say, "Okay, she goes over this really fast, here's a little slower explanation for why this is."*

Many participants, like Bud, view their role as a GTA to supplement the lecture course and as a result, focused on helping students with understanding content that has been taught by the course professor. Laboratory GTAs reported viewing their role as primarily a lab manager, as demonstrated by a quote from Robert, "I don't think that my main role as a lab [GTA] is to be a teacher. That's sort of a secondary role to being a laboratory overseer."

How participants viewed their role in the course they taught may have influenced the way they interacted with students and participated in their teaching role. For example, a chemistry lab GTA may have been discouraged from going beyond the prescribed lab protocol to explain underlying concepts that related to their lab—which would help their students' learning—due to viewing their role as limited to a lab manager.

The second teacher identity theme, *affect*, refers to the feelings participants had about their GTA role. One subtheme was identified: participants felt unprepared for their teaching role. Amanda describes this feeling as follows:

> *I was terrified the first day I walked in here and had to teach. […] I felt good, but at the same time I felt like I was super unprepared because I never had any formal training. No one told me of things that I could do or ways to model teaching, or that there is like six million different ways to teach the same thing. I didn't even know… I had no clue.*

Feeling unprepared as a chemistry GTA could be a result of many different factors (e.g., lack of experience, lack of training, and so on), but it undoubtedly impacts teaching, as demonstrated by Amanda's quote.

*Personal goals* refers to the goals that GTAs had for themselves as related to their teaching role. The most common personal goals were to gain experience teaching and to gain a better understanding of the material, consistent with the goals reported by graduate students in a study by Seymour et al.[7] In the following quote, Faith described her goals of learning the content and gaining experience as an instructor:

> *Two things. I want to be better at the subject of organic chemistry. So the basics are really important. Um, so, you know I taught [organic chemistry I] for an entire year, now I'm teaching [organic chemistry II] this summer, so I get to re-learn all of that content which is great. I think that will be really helpful. But then, I would heavily consider being a faculty member one day, a lecturing faculty, but I don't know yet, so I think teaching is a really nice way to discover whether or not I have a passion for that.*

This theme, *personal goals*, provides insight into motivations for teaching—in addition to financial support[7]—held by participants in this study.

The fourth theme for teacher identity, *desired student perception*, refers to the ways participants hoped to be perceived by their students. Participants strove to be perceived as an approachable resource for students. Allison described this as follows:

> *I try to make it very clear that when I'm in class, I'm really open, that they can ask questions, they can email me, they can come to office hours. I don't want anyone to feel uncomfortable, so if they're struggling with something, they can ask me.*

The ways that participants aimed to be perceived by their students may have influenced their instructional decisions. For example, a GTA that wants to be perceived as approachable will likely act in a friendly manner. Participants' desired student perception may have been influenced by how they view their role in the course—a GTA that viewed themselves as a link between the professor and the students may have found that the best way to take on this role is to be approachable to students.

Participants' teacher identity (summarized in Table 3.2) uncovered in this study provides insight into how chemistry GTAs conceptualize their role. While participants vocalized having the personal goal of gaining experience as an instructor, they did not view themselves as instructors, but rather has a link between professors and students or as a lab manager. Participants wanted students to view them as approachable resources and hoped to gain a better understanding of chemistry content through teaching. GTAs often noted feeling unprepared to teach and having to learn to teach on the spot. This understanding can inform the design of GTA training to support the development of chemistry GTA teacher identities.

**Table 3.2.** Summary of GTA teacher identity themes and subthemes.

| Teacher identity theme | Teacher identity subthemes |
|---|---|
| Role in the Course | A link between students and the professor; supplemental; a lab manager |
| Affect | Feeling unprepared to teach |
| Personal Goals | To gain a better understanding of the material; to gain experience as a teacher |
| Student Perception | An informal, approachable resource |

### 3.8.2 RQ 2: What factors influence the development of GTA teacher knowledge and teacher identity?

To investigate Research Question 2, we further investigated interview excerpts to explore the factors that influence the development of GTA teacher knowledge and teacher identity. We first identified that the challenges related to the instructor role influence GTAs' teacher knowledge. GTAs in this study stated that they struggled when content explanations that they learned as undergraduates were inconsistent with how the current instructor is teaching the course, with understanding the content enough to teach it, with managing many different roles as an instructor, and with managing time. Mallory described her struggle with managing time while trying to cover material and respond to students' questions:

> *There's definitely a big time-management part of teaching. I only have 50 min to get through all of this material, and there are some students whose questions I'm not going to be able to answer fairly, compared to the rest of the students there. There's some students who walk in and they're very confused about everything, and I can't take the time to sit down and talk it out with them, because I have 29 other students who all have questions.*

As Mallory described, the lack of time in class prevented participants from covering content and answering students' questions. To mitigate time constraints, participants guided students to office hours and organized students in groups (classroom management). Amanda described this in the following when asked why she organized her students in groups:

> *I taught you something, I know you can teach your neighbor it and if you can't figure it out, come ask me. [...] Which I found out is actually a teaching philosophy-type thing, which I didn't know until a while later. There were days when I was thoroughly exhausted from teaching lab and just needed to sit down for like a half hour.*

By grouping students and sending students to office hours when needed, participants were also accomplishing their instructional goals of answering students' questions and for students to understand content. In addition to managing time, participants faced challenges centered around understanding course content. Calvin, an international graduate student, described his struggle with teaching a concept he had learned through different representations:

> *There are certain technicalities of representation. [...] I'll give an example if you allow me. If you have a lone [pair on a] nitrogen atom that's conjugated to a double bond, they do here* $sp^2$ *hybridized. [...] My teachers followed more like, the British literature. British UK books and Indian books. They talk about more like, you cannot call it exactly* $sp^2$ *because some resonating structures will represent sp2, some would represent* $sp^3$*.*

Like Calvin, many participants voiced challenges with teaching content in a such a way that was different form how the content was taught and explained to them while they were students. This challenge that participants faced and the challenge of understanding content enough to teach it are especially problematic given that GTAs are expected to be able to effectively communicate content and understand student misconceptions and challenges.[65] Insufficient content knowledge may prevent participants from leading students to answers or scaffolding content (teaching strategies).[8,66,67] Furthermore, experiencing this challenge may negatively affect student learning in laboratory and discussion sections.

In addition, participants drew upon their experiences as students to inform their teaching strategies, similar to GTAs in other studies.[18,26] This is consistent with sociocultural theory of teacher learning—GTAs are learning from their social experiences with others, namely, interactions with previous instructors, to inform their teaching. For example, in a quote included in an earlier section, Allison states that as a student, she found it helpful when her teachers did not answer her questions directly but rather responded with more questions to guide Allison to the answer. Allison reported using this teaching strategy with her students. In some cases, this apprenticeship of observation[68] method of learning to teach can be problematic because as a student, one is unaware of the goals of certain teaching strategies.[8] Students are only privy to their own personal experiences in the classroom and may wrongly assume that their experience is representative of their classmates' experiences.

Because many GTAs receive their only instructional training during graduate school orientation, we analyzed interviews to determine how participants' training influenced their teacher knowledge. We looked at interview responses to the question: “How has this training influenced your teaching?” and determined the teacher knowledge components that were influenced by GTA training. Eleven out of 22 (50%) of the participants in this study reported that GTA training influenced some aspect of their classroom management. Four out of 22 (18%) of the participants reported that GTA training influenced their teaching strategies. Two out of 22 (9%) of participants reported that GTA training influenced the ways they assessed their students, and 5/22 (23%) of GTAs in this study reported that GTA training had no influence on their teaching.

Teacher knowledge has also been shown to be influenced by teacher identity.[45] To investigate this relationship, we looked at each individual interview for instances where an excerpt was coded as a teacher identity component and either teacher knowledge or challenge. The results from this analysis demonstrated a relationship between GTAs' affect and challenges faced by GTAs. Many GTAs noted feeling frustrated or stressed when trying to teach with little preparation. For example, Allison discusses how she struggles with time management (challenge) and feels bad when she does not have time to cover some content (affect):

> *The hardest part for me is that I want to make sure everyone is understanding something, but sometimes we don't have enough time in discussion to go through everything as thoroughly as the students would like, because we have to cover three lectures or the material in only an hour and still give them a quiz on it too, so sometimes it's hard to manage time to cover everything. I don't want to not talk about something that they get quizzed on, because I would feel really bad that I… I think that the managing and the pace of going through material and stuff is something that I struggle with.*

This relationship is consistent with the affect-challenge-skill relationship previously reported.[69] In this study, the authors described the affective component of situations with high or low challenge and high or low skills. Situations in which challenge is high but skills are low—akin to teaching as a graduate student—are linked to an active and unpleasant core affect, as demonstrated in this study.

Another factor that influences the development of the teacher knowledge–teacher identity relationship for GTAs is the minimization of the GTA role. As noted earlier, many GTAs in this study viewed their role as supplementary to the lecture and to serve only as a link between the students and the professor. Brian, for example, had been teaching for over five semesters when we interviewed him. As an undergraduate, Brian found he learned well from a lecture model and appreciated that his professors were available to help, so as a GTA, Brian lectured in his classes and tried to be accessible to his students. When he started teaching as a GTA, Brian was nervous about finding the best way to convey information to his students. When teaching lab sections, Brian gave short lectures on lab procedures and safety concerns, then walked around and watched students as they completed the lab. His instructional goals were for students to remember the big ideas, to make sure lab ran smoothly and students were safe, and for everyone to finish on time. When we asked Brian why these are his goals, he said:

> *So I guess we didn't really have much training on how to teach. We weren't, we weren't really expected to teach much, like we weren't expected to go out there and really influence them and help them out with these new concepts and explain everything to them. [...] So mostly, especially in my early years, I didn't really feel comfortable like trying to expand or, like, do a bunch of like new stuff or come up or give them a lot of information. [...] Mostly a lot of the things we were expected to do, we were supposed to just kind of help them do the lab and once they're done, they could come to office hours and ask questions, but that's like the goal is to help them get the labs done efficiently.*

Because of a lack of social interaction around pedagogy and a departmental culture where GTAs are not necessarily valued as instructors and are not expected to teach, Brian did not perceive his role to be a teacher. Brian's actual perception of his role—as someone to help students finish labs efficiently—discouraged him from explaining and expanding on concepts to support his students' learning. At best, he would answer his students' questions, but did not focus on actually teaching material to his students. When he did teach students about procedures and safety concerns, he used the method he experienced as a student (lecturing). Other GTAs voiced similar perceptions of their role; Vanessa said she is "just another wheel in a larger system," Janice noted, "my role was a self-paced babysitting job," and Jamie comments, "if I were to teach this subject as a whole, I'd need more time, but that's not my job… I am just a lab instructor."

As another example, Grace was a fourth-year graduate student when we interviewed her. As an undergraduate student, she enjoyed doing practice problems and was anxious about her grades but had supportive professors. As a GTA, Grace does not encourage the "must get a good grade" mentality, because she believes it promotes anxiety (like she experienced), and she believes students do not conceptually understand material if they are focused on getting the correct answer. As a result, she views her role as someone to help students work through practice problems. In the semester that we interviewed Grace, she was a GTA for a computational chemistry lab. She mentioned that while students are working on assignments in her lab, she walked around and did her best to help guide students to completing the lab, rather than telling students exactly what to do. However, in order to do this effectively and to anticipate students' questions, Grace tried to complete the lab assignments ahead of time. When asked about constraints that prevent her from teaching the way she would like, Grace responds:

> *There are definitely time constraints because we're expected to do research, and that's supposed to be our primary focus. [...] I like to try to do the labs beforehand, so I can really understand exactly what they have to do, but I don't always have time. I don't really like teaching that much, especially in this context, because I don't have time and I feel like it's not prioritized. We're not supposed to prioritize it, and so therefore I feel like I'm not the best that I could be.*

Later in the interview, Grace notes that if she is not able to complete labs ahead of time, she will work it out with the student, but she states,

> *I don't know exactly the best way to lead somebody in the right direction if I also don't know what the final answer's supposed to be. [...] It's also the process that you have to [understand] which I don't. That's the part I don't always fully understand in this computational class.*

Brian and Grace voice many of the issues we are communicating in this paper. Brian notes that he did not receive much pedagogy training and was not expected to teach. Grace notes that she was expected to focus on research and was not able to prepare for labs as much as she would like. The institutional organization of discussion and laboratory sections—supplemental to lectures—contributes to the view of the GTA role as being supplemental, which hinders the development of GTAs' identities as instructors. Because the culture of chemistry doctoral programs discourages prioritizing teaching (especially when compared with research and course responsibilities), it is implied that an expert graduate student is one who is successful at research and takes on a researcher identity. As a result, chemistry GTAs do not prioritize teaching,[48] rarely identify as instructors, and thus rarely focus on improving their teaching practice.

As shown earlier, there are many factors that influence or hinder the development of GTA teacher knowledge. Chemistry GTA participants drew on previous experiences to inform their teaching, experienced challenges that triggered a negative effect, and are discouraged from spending time improving their teaching and taking on an instructor identity. The results from Research Question 2 demonstrated the specific ways in which these factors serve as influences and inform how influencers can be leveraged in GTA training to promote GTA movement toward student-centered teacher knowledge, discussed further in the section to follow.

## 3.9 Discussion and implications

Chemistry graduate students are expected to teach multiple lab or discussion sections beginning in their first semester of graduate school with very little training or preparation while also balancing academic and research responsibilities. GTAs are in a position where they can influence undergraduate students' learning and interest in STEM disciplines,[40] where GTAs are routinely employed to teach discussion and laboratory sections. Some chemistry departments do not hold GTA trainings at all, and of those who do, the trainings are often overgeneralized, short, and focused on classroom management or logistics of their position.[4,40,70] Without pedagogical training, there is an implicit assumption that content knowledge is enough to teach a subject,[8] which is a belief that GTAs hold.[4] However, content knowledge is only one piece of a larger skill set required for effective teaching.[8,9,66,67] There is a prominent call to improve GTA training in order to better prepare graduate students for their instructor roles.[25,27,71] We assert that a prerequisite to developing a training structure for GTAs is to understand the ways GTAs currently participate in their instructor role and how this is influenced by the context in which GTAs teach.

Through this study we contribute to this understanding; we determined the nature of chemistry GTA teacher knowledge and teacher identity[51] and the factors that influence the development of GTA teacher knowledge and teacher identity. Interestingly and in contrast to other studies of GTAs, participants did not describe GTA peers and graduate school mentors as major influences on their teacher knowledge.[4,7] While further research on this finding is needed, it is perhaps due to the lack of collaboration and social interaction centered around teaching—we might imagine that this would not be true if we were investigating influences on graduate students' research knowledge.[72] Kelly[51] echoes the argument that the potential for constructing teacher knowledge is increased when teachers engage in collaborations involving problem solving, sharing ideas and perspectives, creativity, and innovation.[73] As such, our first and most central recommendation is to allow for these collaborative spaces to exist between GTAs by extending GTA training past orientation and well into graduate students' first year of teaching.[16,17,40] Our remaining recommendations for training would ideally be situated within a prolonged collaborative space.

Sociocultural theories of teacher learning assert that teachers draw on existing knowledge to inform their teaching, and teachers continuously develop this existing knowledge base as they engage in teaching in their own particular circumstances.[51,74] In the project presented herein, we characterized our participants' knowledge base for teaching and learning. Figure 3.1 displays this and relationship between chemistry GTA teacher knowledge components. GTA teacher knowledge unveiled here can serve as a foundation for chemistry GTA training. Within a prolonged training, GTAs can be exposed to high-leverage practices that relate to GTAs' current knowledge for teaching.[75] For example, GTAs in our study report that they know students are different—they have different goals, interests, and learning styles. Chemistry GTA training could leverage this knowledge in explaining that students learn in different ways and teaching in different ways is important in supporting their learning.

Similarly, the connections evident in our participants' knowledge bases for teaching and learning can be leveraged in GTA training. For instance, GTAs in this study reported instructional goals (students learn content, answer students' questions, demonstrate relevance of chemistry, and engage students) which influenced their choices of teaching strategies (lead students to answers, scaffold content, incorporate relevant examples of chemistry). This relationship between instructional goals and teaching strategies could be leveraged in GTA training by informing GTAs of the instructional goals of their teaching sections and exposing GTAs to teaching strategies that help achieve those goals—one should not be discussed without the other. Engaging GTAs in the practice of identifying specific achievable goals, methods to accomplish their goals, and methods to assess whether their goals were achieved should be a focus of GTA training.

The challenges that chemistry GTAs face provide insight into the complexity of the GTA teaching practice.[76] With the exception of the challenge regarding inconsistent explanations of content, the challenges identified by GTAs in this study echo the literature on science teacher learning,[76–78] and are unsurprising given that chemistry GTAs rarely receive support for teaching.[4] Researchers have found that discussing challenges increased teachers' confidence in risk taking, enhanced students' and teachers' scientific literacy, and helped to develop teacher's knowledge of their profession.[79] Thus, first-year chemistry departmental GTA training should include a discussion of anticipated challenges associated with the GTA role, and this discussion should continue throughout the semester and evolve as incoming GTAs experience their own challenges.

Within a semester-long training, opportunities for GTAs to discuss their challenges and reflect on their practice with the support of more experienced GTAs or other instructional faculty and staff provides a space for GTAs to develop their identities as instructors and their teacher knowledge.[45,51]

GTAs in this study and others use their previous experiences as students and instructors to inform how they teach.[18,26] Similarly, pre-service science teachers have reportedly struggled with moving past what they have experienced and have found to be successful,[80] and a great challenge for teacher education programs is to encourage teachers to see beyond their experiences as students.[78] It is thought that this challenge originates from the resistant core beliefs of teaching that are held by learning, new, and experienced teachers, including GTAs.[81] Thus, in chemistry GTA training, teaching beliefs should be surfaced, challenged, and developed, as they are in K-12 teacher training programs.[82]

A semester-long departmental GTA training run by faculty or staff may also alter the research-focused culture of STEM departments perceived by GTAs. As noted in the study presented herein, GTAs rarely view themselves as teachers, but more so as tutors in discussions or as managers in laboratories. This opinion is likely due to how professors and research mentors interact with GTAs[48]—social interactions and recognition by others has repeatedly been shown to be a strong influencing factor on identities in STEM.[83] Chemistry GTAs play a crucial role in undergraduate STEM education and are in a position to greatly influence the interest and retention of undergraduate students. However, in order to fulfill this role, GTAs must do more than tutor or manage labs—they must focus on supporting students' learning of chemistry. GTAs work in environments that prioritize research over teaching,[4,5,48] so they do just that. Lane et al.[48] describe this doctoral culture as a blizzard that graduate students need to navigate through in order to develop their teacher identities. In an environment that places more focus and value on teaching, the blizzard may calm, and GTAs may be more encouraged to place more focus and value on their GTA role.[84]

In summary, a semester- or year-long chemistry GTA training that includes collaborative spaces focused on (a) discussing experienced challenges, (b) confronting beliefs, (c) reflecting on teaching, (d) aligning of GTA goals, teaching strategies, and assessments, and (e) that builds upon GTAs' previous experiences and current knowledge may be a viable option to support graduate students in their roles as instructors which will thus help the thousands of undergraduate students taught by GTAs. However, the GTA training structure will crumble without enthusiastic, committed facilitators. In accordance to sociocultural theory of teacher learning, GTAs learn to focus on research and neglect their teaching role if that is the culture of their department.[51] In order to improve participation in instruction, GTAs must learn to prioritize teaching, which requires a shift in departmental culture.

## 3.10 Supporting information

### 3.10.1 Graduate student interview on teaching experience

1. What are your current career ambitions?
2. Could you tell us a little about your previous education? (What/where/when?)
3. Tell us about your undergraduate chemistry courses – what were they like?
    a. What did you (or didn't you) enjoy most about these courses?
    b. What features of these classes helped you learn (or inhibited your learning)?
    c. What were your interactions with instructors/faculty like in these courses?
    d. What were your interactions with your peers like in these classes?
    e. In what ways have these courses/your experience as a student influence how you teach (or will teach) chemistry?
4. Do you have any prior teaching experience before your GTA role?
    a. What was it like?
    b. How does it compare to teaching here?
    c. What have you found to be challenging/what concerns do you have about teaching here?
    d. What have you found to be helpful?
5. Have you had training to prepare you for teaching – at this university or previously?
    a. What was it like?
    b. How has your training influenced how you teach (or will teach) chemistry?
6. Have you read any literature about teaching and learning?
    a. (if yes) What have you read?
    b. (if yes) How has it informed your teaching?
7. What do you hope to gain from your teaching?
    a. How do you view your role as an instructor in lab or discussion sections?[41]
    b. What do you hope students will gain from these sections?
8. While you are teaching, what are your goals?
    a. Why?
    b. How do you accomplish these?
    c. How do your goals for teaching compare with broader course and instructor goals?

    d. How do you know when your students understand material?[41]
    e. When you have a student really struggling to understand a concept, how do you respond?
    f. How do you decide when to move to a new topic?[41]
9. Describe your teaching style or how you think you'll approach teaching if you haven't yet.
    a. How did you arrive at this style?
    b. What do you take into consideration?
    c. What are specific goals of this style?
    d. Could you give an example of when you have employed this teaching style?
    e. Are there any constraints that prevent you from teaching the way you'd like to?
    f. How do you/could you navigate these constraints?
10. When you teach, what is your goal in representing science as a whole?
    a. How does this fit within teaching the course?
11. What does it mean to "do science"?
    a. How does science progress/evolve?
    b. How/when do you think people learn to do science?
    c. How does this influence your teaching?

## 3.11 Acknowledgements

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# Chapter 4

# Learning in Isolation: A Case Study of Three Chemistry Graduate Students' Development as Instructors

## 4.1 Initial remarks

This chapter constitutes the second of two studies for which the sociocultural theory of teacher learning was used as a lens to understand chemistry GTAs' experiences. This theory was used in conjunction with a case study methodology where the experiences of three chemistry GTAs were deeply investigated over two or three semesters of teaching. The case study approach provided a more holistic understanding of how the context in which GTAs teach influenced their teacher knowledge and identity and how their teaching adjusted over time. Each GTA participant was in their first semester of graduate school when the study began, and one participant was an international student simultaneously adjusting to a new culture. Throughout each semester, each GTA was observed four times as they taught their lab or discussion session. After each observation, a researcher conducted a post-observation interview to gather the GTAs' goals for the session, perceptions of how the session went, and additional context. Each participant's data set (observations and interviews) was qualitatively analyzed to describe the nature of each observed class session, how GTAs taught their students, and factors that influenced their teaching. This analysis provided insight into each GTAs' teacher learning.

While each GTA taught in the same chemistry department and worked toward the same chemistry doctoral degree, they each had unique experience prior to and during graduate school that influenced their teaching. GTA participants' teacher identities seemed to be shaped by the structure of the course for which they taught and the course professors' expectations of how GTAs would fulfill their role. For example, one GTA taught within a specific course structure in which she was expected to cover specific content in a prescribed way. This participant felt it was risky to deviate from this structure, and thus viewed her role as someone to help students learn in this way.

Similar to findings in Chapter 3, the GTA participants drew on their prior experiences as students or as instructors to inform their teaching. These experiences led GTAs to use a comfortable teaching strategy—one they knew “worked” based on their own experiences—when they were asked to teach without guidance. We observed that GTAs modified their teaching based on their in-the-moment experiences with their students. For example, when students struggled to complete a specific problem, GTAs reflected on this experience and adjusted how they taught their classes in the future. This self-reflection was an influence on our GTAs’ development as teachers. Notably, GTA participants rarely discussed interactions with other peers or mentors in the department centered around teaching. Collegial support may enable teachers to implement teaching strategies they may not otherwise attempt, but the isolating and research-focused environment GTAs work within did not provide this support for our GTA participants. Findings from this work were member checked with the three GTA participants to ensure our interpretations of collected data aligned with their experiences.

Insights suggest that while GTAs develop their teaching based on independent and unstructured reflections of their teaching experience, their development would be accelerated by a structure in which GTAs have access to support from colleagues. Additionally, these results shed light on potentially limited teacher learning that occurs in GTAs’ experiences, which conflicts with the common assumption that teachers with more experience hold more teacher knowledge. The author makes specific recommendations for both GTA training and further research on GTAs at the end of this chapter.

This chapter is being prepared as a publication to be submitted to a science education research journal. Dr. Nicholas Potter contributed to data collection for two participants. Rebecca Fantone and Jordan Tyo assisted with preliminary data analysis. Jordan Tyo analyzed one participants’ case and wrote portions of the manuscript. Jeff Spencer wrote portions of the manuscript and contributed to the final organization of the manuscript. All remaining work, including data collection, data analysis, member checking, and manuscript writing were completed by the author.

## 4.2 Abstract

Graduate teaching assistants (GTAs) serve important roles in undergraduate STEM education teaching discussion and laboratory sessions. Although they support student learning, graduate students’ progress towards degree completion at research-focused institutions is typically based on their research productivity. As a result, GTAs rarely spend time developing their teaching skills. While studies explore some teaching knowledge held by chemistry GTAs, little is known about the strategies they employed when teaching and how their teaching develops over time. To investigate the ways GTAs teach in their unique social contexts, we conducted observations and interviews over multiple semesters with three chemistry GTAs in their first year of graduate school when the study began. With the lens of sociocultural theory of teacher learning, we used a case study approach to characterize these GTAs' teacher learning. We describe the social structures GTAs work within and the resources GTAs draw on throughout their teaching experiences. We found that course structure heavily influenced GTAs' teacher identities. Their prior experiences as students and teachers formed the basis of their teaching, which evolved over time as GTAs individually reflected on their experiences in the classroom. Participants rarely discussed social interactions with other GTAs or support from staff or faculty for implementing new teaching strategies. This study provides a more complete understanding of first-year GTAs' teaching experiences and has implications for how departments can better support GTAs' development of teaching skills.

## 4.3 Background

Graduate teaching assistants (GTAs) serve important roles in higher STEM education. While professors, lecturers, and postdoctoral fellows teach the lectures for large-enrollment courses like general chemistry and organic chemistry, GTAs often lead discussion and laboratory sessions. In these sessions with 20-30 students, GTAs introduce and guide students through experimental protocols, teach new content, and review lecture material. Due to the smaller discussion and lab class sizes, GTAs generally have more facetime with undergraduate students than the professors who teach the corresponding lectures.[1] Thus, undergraduate STEM education hinges on graduate students' engagement in their teaching role. However, graduate students' teaching responsibilities are peripheral to their progress towards graduation, which often hinges on successful research.[2]

STEM doctoral students typically join a research lab during their first year of graduate school and must complete a certain amount of research before obtaining their Ph.D. Professors who lead research labs are also under pressure to complete research to satisfy grant and promotional requirements. A GTA participant discussed their view of the role of GTAs in a study by Luft et al.: to take the burden of teaching off of research-focused faculty members.[3] The GTA then says, "[GTAs] are important because they allow the research agenda to move forward" (pg. 222).[3] In other words, GTAs can take on undergraduate teaching responsibilities, which allows research faculty to spend more time preparing for and conducting research. Although a primary goal of graduate school is to prepare students to become independent researchers who contribute to the construction of new knowledge,[4] one in three STEM Ph.D. students will become an instructor or faculty member who teaches in some capacity.[5]

The prioritization of research in doctoral programs contributes to a research-focused culture for GTAs.[3,6,7] GTAs perceive that this culture obscures their opportunity to develop identities as teachers.[8] Lane et al.[8] characterized life science doctoral students' teaching identities, mentioning that GTAs are more likely to develop salient and stable teaching identities if they participate in teaching professional development, experience recognition as a teacher, have teaching mentors and like-minded peers, and experience independent teaching structures. Unfortunately, these opportunities and this recognition are uncommon in a culture that GTAs perceive to "marginalize those interested in teaching" (pg. 158).[8]

Zotos et al.[9] explored the implications of research-focused doctoral programs on GTAs' development of teaching knowledge and identities. They found that GTAs viewed themselves as lab managers and tutors—not as teachers—and therefore did not spend time developing teaching skills or knowledge because they were discouraged to do so. GTAs in this study and others drew strongly on their experiences as students to inform the way they taught.[10,11] Many GTAs learned through traditional, directive teaching methods, such as lecturing. As a result, GTAs aim to transfer information to students and teach through similar directive methods.[3,9,11,12] GTAs also work in autonomous instructional environments where feedback from staff or faculty on teaching is rare.[3] Thus, without exposure to and proper support for the implementation of evidence-based teaching methods, GTAs often perpetuate the traditional style of teaching, which persists through their careers as faculty members.[13]

Following STEM departments' overarching goal of moving toward evidence-based instructional practices,[14] focus on the unique and understudied population of GTAs is growing through the design, implementation, and evaluation of training modules.[15,16] Much of the research on chemistry GTAs focuses on their content knowledge[17–20] and teaching knowledge[3,9,21–24] from an individual perspective. Looking at the teaching knowledge held by GTAs is important for understanding what informs GTAs' teaching, however, instructors often overestimate the amount of reform in their teaching when self-reporting.[25] Hence, many studies suggest researchers conduct classroom observations to investigate the ways GTAs put their knowledge into action. So far, three studies examine the ways chemistry lab GTAs teach their sessions through observations.[22,26,27] Velasco et al.[27] developed an observation protocol to characterize chemistry lab GTAs' instructional practices. The authors used this protocol when observing GTAs who taught traditional general chemistry lab courses. They identified four instructional styles that describe GTAs who (1) wait for students to approach them, (2) are constantly being called on by students for help with the lab experiment, (3) spend most of class observing students, and (4) constantly initiate conversations with students, probe their thinking, and praise their work. Current and Kowalske[22] found that GTAs' classroom discourse depends on the type of instructional mode. More specifically, GTAs' discourse was more student-centered in inquiry labs than in expository labs.[22] Duffy and Cooper[26] investigated whether project-based lab GTAs' beliefs of their duties aligned with (1) how they taught their classes and (2) the lab coordinator's expectations for GTAs. For the most part, GTAs understood what was expected of them and taught this way in their classes. When GTAs' beliefs about their role misaligned with the lab coordinator's expectations, it was often due to GTAs' lack of confidence in students (e.g., GTAs believed they needed to be more hands-on when students worked with apparatuses that were new to the students).[26] While these studies provide valuable insight into GTAs' teaching, they do not examine the larger social structures and resources surrounding GTAs as they develop in their context. Thus far, no studies have looked at chemistry GTAs' teaching over time. The goal of this research is to extend the literature by focusing on these aspects of GTAs' teaching.

Here we present a case study of three chemistry GTAs as they develop their teaching through observations and reflective interviews over at least two semesters of teaching. We study how these GTAs teach their lab and discussion sessions and consider the influences of the social structures surrounding the GTAs teaching. Since GTAs tend to work in a uniquely isolating and research-focused culture,[3,8,9] conducting a case study allows us to deeply investigate the factors that influenced each GTAs' teaching. We use the sociocultural theory of teacher learning[28] as a lens to investigate GTAs' teacher identity, teaching practice, teacher knowing, and teacher knowledge over time. The following research questions guided this work:

(1) What sociocultural aspects of GTAs' environments inform their teacher learning?

(2) How does a GTAs teacher learning shift as they gain teaching experience in their social context?

Exploring these research questions will provide a more holistic perspective of GTA teacher development within their unique social context and allow for suggestions to focus on developing support structures surrounding GTAs.

### 4.4 Theoretical framework

We approached our study using the sociocultural theory of teacher learning.[28] Because this theory considers the social, historical, and physical contexts in which teachers learn to teach, it is particularly useful when investigating GTAs who learn to teach in specific contexts. Many social factors can influence a teacher's developing expertise, such as peers, mentors, job expectations, and resources. Knowledge the teacher gains can be distributed across these factors. Furthermore, the definition of expertise also depends on the teacher's social context. For example, teachers in different contexts will have varying professional expectations depending on in-school professional support, administrative structures, students and their cultures, and resources offered in the classroom. Kelly[28] describes four components of teacher learning: teacher identity, teacher knowledge, teacher knowing, and teaching practices. We will provide examples of each using a hypothetical teacher.

*Teacher identity,* in a social model, refers to the ways teachers view their professional roles in their particular social contexts. Teachers' identities are influenced by interactions with others and evolve. For instance, a teacher could be interested in cooperative learning[29] because of their individual beliefs in how learning occurs and because their school has evaluation criteria that ask the teacher to engage in these sorts of activities. As they gain expertise within their school context, they may feel an increasing sense of comfort and freedom in trying new teaching methods that align with their individual and organizational beliefs. This increase in their agency to try new methods could be due to an increased awareness of how their role fits into their school's social structure and may be reinforced as they receive recognition from members of this social structure.

The term *teacher knowledge* describes teachers' knowledge base for teaching and learning and can be influenced by teachers' prior experiences and formal education. Teacher knowledge includes both content knowledge and pedagogical knowledge and is constantly evolving as teachers engage in teaching practices. For instance, our hypothetical teacher could have formally learned about cooperative learning within their teacher education program. They also could have engaged formally in programs that support cooperative learning from professional developments, such as attending a POGIL workshop[30] when they were a young teacher. Both experiences contributed to a body of knowledge that expands as they learn more about these types of teaching techniques. Kelly[28] also mentions a *tacit knowledge* that is a form of teacher knowledge learned through years of engaging with practices in a specific context. In this example, while implementing POGIL over years, the teacher learns and adapts POGIL structures based on interactions with students.

The term *teacher knowing* describes the in-the-moment actions teachers make that are influenced by their own prior experiences, available resources, and their students' knowledge. Upon learning about POGIL through formal training, this hypothetical teacher may start to implement the activity in the classroom. While they implement the activity, students may generate an alternative conception to a topic that the teacher notices as a pattern in the class. The teacher may stop the class and hold a whole-class discussion to clarify students' understanding before moving on. The class continues, and the teacher uses a similar structure to gauge if other classes have similar ideas. In this example, the teacher uses the students as resources to learn whether they understand the material and shifts to the structure of the course to allow students to explore difficult topics further. The teacher could also shift later classes based on these in-the-moment decisions.

*Teaching practices* refers to teachers' engagement in the professional practices and norms of teaching in their particular context. As stated above, what it means to be an expert teacher depends on the context in which they teach. Similarly, in certain contexts, different teaching practices may be valued. In other words:

> "Teachers' engagement in the working practices of schools and the associated discourses and ways of thinking which help define school life make it more likely that they will have particular expectations of what it is to be an expert teacher and privilege particular problems which expert teachers might seek to address." (p. 512)[28]

This professional activity is in combination with the teaching practices that teachers use in the classroom with their students. Our hypothetical teacher may discuss how they implemented their POGIL activities with other teachers of the same subjects, asking for their impressions, advice, or implementation strategies to inform their practice. This could occur formally in professional development settings or teacher learning communities,[31] or informally, such as at a gathering of colleagues after the school day concludes or between class periods. In either scenario, the teacher draws upon their extended social network to inform how to implement formalized teaching strategies in their specific context. *Teaching practices* also extends to the implementation of the POGIL activity in their classroom and the teachers' use of student data to continually adapt the resource to fit their context.

## 4.5 Methods

### 4.5.1 Context

We conducted the study in the chemistry department at a large research university in the Midwestern United States. The department hires graduate students to teach discussion sections or lab sections as a source of funding, similar to many large research institutions.[32] The department assigns GTAs at the beginning of each semester based on availability (e.g., the number of GTAs needed for a class and whether graduate students are available during scheduled sessions). All graduate students attend a week-long orientation in August before their first semester of graduate school. Orientation includes two days of teacher training, where GTAs receive a generalized overview of classroom management, logistics, and safety.

During the semester, course professors in this department hold weekly staff meetings to review content and to inform GTAs of course logistics (e.g., topics covered, major assessments). Additionally, the university employs an online anonymous student feedback system twice per semester, once during the middle of the semester and once at the end of the semester. The feedback system asks undergraduate students to respond to a standardized series of Likert-scale statements (i.e., strongly agree to strongly disagree) about their instructors. The students may add written feedback at the end of the survey. Sample statements in this survey include, "Students feel comfortable asking questions in class" and "X GTA provides helpful feedback on assignments." Most professors of introductory-level courses, where many first-year GTAs teach, select one or two experienced GTAs to mentor younger graduate students for the course during that semester. These graduate student mentors taught the class before and demonstrated leadership in the class. Graduate student mentors have a variety of duties depending on the course that they teach, such as checking on lab GTAs during three to four-hour lab sessions or filling in for GTAs that are sick. All graduate student mentors meet with first-year GTAs once per semester to review their midterm student feedback.

### 4.5.2 Participant selection

The GTAs in this study participated in a previous study about graduate student teacher knowledge and identity.[9] The data set from the previous study comprised of interviews with 22 GTAs. After the initial interviews, six GTAs volunteered to participate in video observations. Of the six initial participants, three agreed to participate in a second semester of observations (Mallory, Calvin, and Abby; pseudonyms). One participant (Abby) agreed to participate in a third semester of observations. When we conducted the first observations, Mallory, Calvin, and Abby were in their first semester of graduate school. Table 4.1 summarizes the data we collected from participants, forming what we used to construct the case studies and their teaching responsibilities that we observed in this study. Mallory's, Calvin's, and Abby's initial interviews, a modified teacher beliefs interview[33] that was a part of the data set in the previous study,[9] was used in this study to provide background information for each participant, though not formally analyzed.

**Table 4.1.** Courses taught, when each course was taught, and the number of observations per semester for each participant.

| Participant | Undergraduate Institution | Semester 1 | Semester 2 | Semester 3 |
|---|---|---|---|---|
| Mallory | PUI | General chemistry discussion<br>Fall 2016<br>*4 observations*<br>*4 interviews* | General chemistry discussion<br>Winter 2017<br>*3 observations*<br>*3 interviews* | – |
| Calvin | R2 (International) | Organic chemistry I discussion<br>Fall 2016<br>*3 observations*<br>*3 interviews* | Organic chemistry II lab<br>Winter 2017<br>*4 observations*<br>*4 interviews* | – |
| Abby | R1 | Biochemistry discussion<br>Fall 2017<br>*4 observations*<br>*4 interviews* | Inorganic chemistry discussion<br>Winter 2018<br>*3 observations*<br>*3 interviews* | Biochemistry discussion<br>Fall 2018<br>*4 observations*<br>*4 interviews* |

### 4.5.3 Data collection

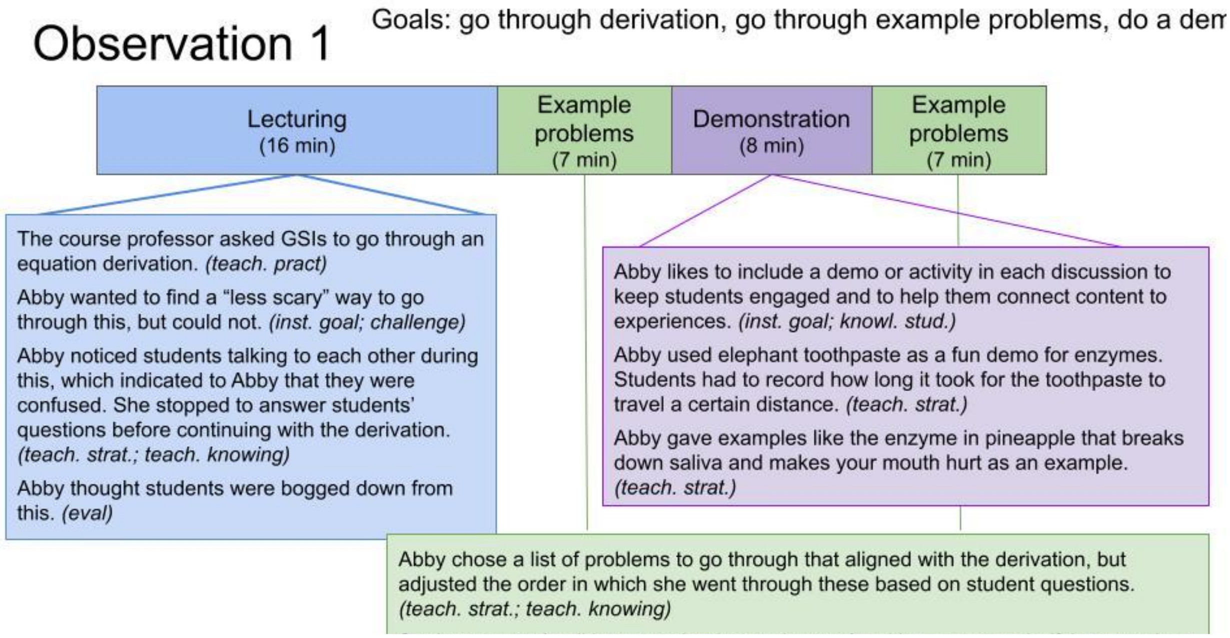
We used cameras and an audio recorder to capture observations of Abby, Calvin, and Mallory teaching. To capture as much of the classroom as possible (e.g., the students, the instructor, and the chalkboard/projector screen), we placed a stationary camera at the back or side of the classroom. To capture clear audio of the GTA's interactions with students, GTAs wore a lapel microphone with an audio recorder. Initially, we tried to capture GTA and student interactions using a small, wearable camera secured to the GTAs' lab glasses. This was useful in laboratory settings where we observed Calvin as the stationary camera could not fully record the complex activities of the students. The wearable camera allowed us to see what GTAs focused on in the laboratory. The wearable camera did not add any depth to the data in GTAs' discussion sections and thus was not used in the analysis. This approach allowed us to deeply investigate the experiences of novice GTAs as they developed as teachers throughout graduate school.

To select an observation time, GTAs and researchers selected sessions where the researcher was available to collect data. Dates were intentionally chosen to span three months during each semester to capture GTA teacher learning over time. For each observation, to reduce the impact of having an external person observing the GTA, a researcher came to the class early to set up the equipment, left the room for the duration of the discussion, and returned at the end of the session to collect the equipment. Table 4.1 contains information on when we conducted GTA observations, the number of observations we collected each semester, and the courses taught by each participant. Within 24 hours of the observation, we conducted and audio-recorded a semi-structured interview, which we label the post-observation interview. The goal of the post-observation interview was to capture the GTAs' perspective of how the observed session went and any additional context for the session. The interview contained questions such as "How did your section go?" "What were the aims of your particular section?" "What parts of your section could have gone better and what parts went particularly well?" and GTAs responses prompted additional questions to clarify their experience. We include our interview protocol in Supplementary Information. We used Rev.com and Otter.ai to transcribe all post-observation interviews, and the researchers verified the transcripts once they were processed. Each participant and their students consented to this study, and we obtained IRB approval before collecting data.

### 4.5.4 Data analysis

We analyzed video data and post-observation interview transcripts using NVivo 12 Pro. During the first coding cycle, we time-stamped video recordings to inductively identify sections of each session (i.e., when the GTA was lecturing, when students were working, etc.). This first-round of coding primarily provided insight into GTAs' teaching practices regarding how they taught their sessions. We coded sections based on the natural cadence of the lesson, focusing on teacher moves of the GTAs and interactions with students. For instance, in Abby's first observation, she began the session by lecturing about an equation derivation and used the chalkboard to work through the derivation, then ran through example problems with her students, did a demonstration, and then continued to work on example problems. The sections of this session were coded as lecture, example problems, demonstration, and example problems. The timeline for this session is included in Figure 4.1, and all observation summaries are included as Supporting Information.

While we coded the observation data, we constructed observation summaries (Figure 4.1) for each observation using Microsoft PowerPoint to manage and organize the data.[34] The observation summaries helped reduce the large amount of data into digestible chunks while also providing a way to see changes over time for one participant. We created a visual timeline of the observed session using the video recording timestamps to provide an overall summary of the session timeline in each observation summary. The timestamps corresponded to the first-round coding of each section of the lesson, including lecturing, going through example problems, and giving students time to work on problems. From the observer's perspective, we added more details



The course professor asked GSIs to go through an equation derivation. *(teach. pract)*

Abby wanted to find a "less scary" way to go through this, but could not. *(inst. goal; challenge)*

Abby noticed students talking to each other during this, which indicated to Abby that they were confused. She stopped to answer students' questions before continuing with the derivation. *(teach. strat.; teach. knowing)*

Abby thought students were bogged down from this. *(eval)*

Abby likes to include a demo or activity in each discussion to keep students engaged and to help them connect content to experiences. *(inst. goal; knowl. stud.)*

Abby used elephant toothpaste as a fun demo for enzymes. Students had to record how long it took for the toothpaste to travel a certain distance. *(teach. strat.)*

Abby gave examples like the enzyme in pineapple that breaks down saliva and makes your mouth hurt as an example. *(teach. strat.)*

Abby chose a list of problems to go through that aligned with the derivation, but adjusted the order in which she went through these based on student questions. *(teach. strat.; teach. knowing)*

**Figure 4.1**. The observation summary for Abby's first observation.

for each portion of the session, taken from both the video recording and the post-observation interview to the observation summary.

Since this work builds upon previous studies about chemistry GTAs' teacher knowledge, we provisionally coded[35] the post-observation interview transcripts using the codebook from the study above aimed to capture GTAs' teacher knowledge and identity.[9] The codebook included six codes—instructional goals, knowledge of students, classroom management, teaching strategies, assessment of students, and challenges. We also added the code *teacher knowing* to capture when our participants reflected on how interactions with their students influences adjustments in their teaching. The unit of analysis for the post-observation interview was at the paragraph level, and each paragraph could receive multiple codes if warranted. For instance, in Abby's second semester of teaching, she described her motivation for creating resources for her students after the course professor directed students to a research article (referred to as a 'paper') for a specific course topic:

> *I'm trying to be the middle ground because [the course professor's] lectures are very vague and they're all pictures. The paper is very dense and has a lot of details that they don't need. So I like to provide them with a resource in between that tells them the details of what the paper gives, but parses out the important details.*

This statement was coded as both instructional goals (making content more accessible) and teaching strategies (providing and using the resource in class).

The analysis continued with the first and third authors coding a subset of interviews and discussing agreements and discrepancies. These conversations continued until we reached consensus,[35] with discussions on how the tenets of the sociocultural theory of teacher learning related to the codes in the study above. Through comparative analysis, the first and third authors identified overarching, recurrent themes[36] from the observations related to GTAs' teaching and factors that influenced GTAs' teaching. This analysis resulted in four themes: the influence of course structure, observed teaching strategies, consideration of students, and reflection on teaching. Each theme provides insight into components of the sociocultural theory of teacher learning (teacher knowledge, teaching practices, teacher identity, and teacher knowing)[28] for our GTA participants (see Table 4.2), which is described further in the discussion section.

After refining the codebook using the post-observation interviews, we then deductively applied the codes to the observation summaries to look for connections between GTAs' comments in the post-observation interview and how they conducted the lesson. We constructed cases for each participant with these codes and examples in mind. In the summer of 2021, the first author contacted participants via email to initiate a member checking process, which allowed participants to read through early interpretations and provide insight into further analysis.[37] We sent each participant a document containing the results related to their case and included any quotes we intended to include in the final manuscript. We asked participants to recall their time as a first-year GTA and to comment in the document on whether our summary aligned with their own experiences. We prompted participants to add additional context, clarification, or alternative language wherever they felt it was needed. We asked participants to complete this task and send us the document with their comments and edits 24-hours before meeting virtually. During the meeting, the first author and each participant talked through the results, discussed the participants' comments, and clarified as needed. The results section of this manuscript reflects clarifications, suggestions, and further insight into their experiences as GTAs.

**Table 4.2.** Emergent themes, descriptions, and connections to sociocultural theory of teacher learning.[28]

| Emergent Theme | Related Tenet of Sociocultural Theory of Teacher Learning | Description |
|---|---|---|
| Influence of Course Structure | Teacher Identity | How the GTA viewed their role within the structure of the course, GTAs' perceptions of their job expectations |
| Teaching Strategies | Teacher Knowledge | GTAs' knowledge of how to teach content (e.g., through lecturing or assigning practice problems in small groups) |
| | Teaching Practices | How GTAs taught their sessions |
| Consideration of Students | Teacher Knowledge | GTAs' knowledge of how students learn, what students typically struggle with, students' interests, students' goals, etc. |
| | Teacher Knowing | When GTAs' teaching in-the-moment was influenced by their knowledge of students (e.g., students' interests outside of class influenced teaching) |
| Reflection on Teaching | Teacher Knowing | When GTAs reflected on their experiences teaching to inform future teaching actions |
| | Teaching Practices | When GTAs' reflected on their experiences with a peer (e.g., through conversations with a graduate student mentor) |

### 4.5.5 Conception of validity

Inherent in a case study is a small number of participants, which allows for a deeper understanding of our participants' context and culture. Our results reflect the GTA population of the specific context where we conducted the study. While the specific results might not be generalizable, we believe that the theoretical construct of sociocultural theory of teacher learning, and the implications thereof, are transferable between contexts.[38] Since we seek a highly contextualized description of GTAs experience, we operate under a constructivist validity paradigm[39] where the authors' biases are inherent in the data collection, analysis, and report. With this in mind, throughout the methods and discussion, we seek to provide a rich description of how we conducted the study and the experiences and perspectives of the participant GTAs. This included having a long-term relationship with each participant and allowing instances in which they could clarify their experiences and affect the analysis. We also paid close attention to instances where the sociocultural theory of teacher learning did not apply to this population and reported these instances in our results section. Finally, one of our research questions addressed how GTAs' teacher learning shifts as they gain experience. Two or three semesters of teaching experience may not be enough time to observe teacher learning in this setting. GTAs likely continue learning as they continue to teach throughout their graduate school career. A study that follows GTAs for additional teaching semesters may provide more insight into their teacher learning.

### 4.6 Results

This study aimed to investigate and describe three first-year chemistry graduate students' teacher learning.[28] In addition to a modified teacher beliefs interview at the start of graduate school,[9,33] we conducted video observations and post-observation interviews over multiple semesters to capture our GTA participants' teacher learning.[28] In the results section, we present each GTA as a case, organized by themes: course structure, teaching strategies, consideration of students, and reflection on teaching. Each case begins with background information about that participant and ends with a case summary.

#### 4.6.1 Mallory

**Background.** Mallory started graduate school after completing her undergraduate education at a primarily undergraduate institution. Mallory enjoyed the small size of her undergraduate chemistry department because she was able to interact with other students and professors regularly. As an undergraduate student, Mallory tutored for general chemistry and a variety of math classes for several years. She worked with students both in small groups and one-on-one. Mallory liked working with students from various academic backgrounds and helping them think about course content in a way that is relevant to them. She said:

> *Part of the thing about my school was that it's math and science focused, so there's no non-math or science major there. […] You have a lot of different mathematical and scientific backgrounds that you're really trying to speak to, and, because I like to think about things in terms of different mindsets, like I can think about things in physics or in biology, it was really cool to try to get those students to see why it might be relevant or applicable to them, or to find an easier way for them to think about it.*

In terms of her personal goals related to her GTA position, Mallory hoped to gain comfort in the material, know what questions to ask students, and gain experience interacting with students younger than her. At the start of graduate school and while we collected data for this study, Mallory was undecided about working in industry or teaching at a primarily undergraduate institution after completing her Ph.D. During our member checking meeting, Mallory informed us that she had taken a chemistry professor position at a primarily undergraduate institution.

**Course structure.** Mallory taught general chemistry discussion during her first year as a graduate student. About 1,400 undergraduate students enroll in this course in the fall semester (about 600 in the winter semester), and the lecture session, which meets three times per week, is typically taught by a course professor and two or three postdoctoral fellows. Fifteen to twenty GTAs are hired to teach supplementary discussion sections with 20-30 students for one hour each week. In the two semesters we observed Mallory teaching general chemistry discussion, the course professor had specific expectations for how GTAs should lead their sessions. The course professor provided practice problems and weekly quizzes, and GTAs were expected to organize students in groups to work on those practice problems for 25 minutes, review the problems as a full group for ten minutes, and then give students ten minutes to complete a quiz.

In all seven of Mallory's observations, she followed the structure provided by the course professor—small group work, full group discussion, quiz. The course professor also expected GTAs to allow students' questions to guide the content covered in sessions. Mallory expressed a tension between the course professor's expectations and her experiences in the classroom:

> *According to the professors in charge, the students are completely supposed to dictate the content and you're not supposed to do anything, other than answer questions that they provide you. That doesn't always work with most of the students because they're freshman and they're not used to this kind of learning and some of them don't feel that comfortable asking questions. I tend to do a hybrid approach, where I base it mainly around student questions but then also add in things that I think are important along the way.*

Mallory felt a strong responsibility to teach her students well, and because each discussion section met only once per week, she was apprehensive to deviate from this given structure. Mallory explained:

> *It's scary to try new things, and it's even scarier when the stakes feel really high. And I will argue that even though teaching isn't valued [by the department], for the people who do value teaching, when you only have twelve sessions to prove yourself, the stakes are really high. And you don't want these students to do poorly and feel like it's your fault.*

Mallory's goals as a GTA were (1) to help students develop transferable problem-solving skills and (2) not to leave her students more confused than when they entered her classroom. The latter goal aligned with Mallory's apprehension of deviating from the set structure to teach her students well. Mallory most often discussed this goal and said:

> *Don't confuse them more. [...] My main goal is, if they walk into the classroom and they're not confused, I don't confuse them. [...] Some students will go to lecture, and they will leave knowing the information. And I [do] not want to have a negative impact on those students while trying to give the ones who had trouble comprehending the information a different way to think about the problem.*

**Teaching strategies.** Mallory adhered to the structure set by the course professor (25 minutes for group work, ten minutes reviewing content, ten-minute quiz), so all that we describe in this section was within the boundaries of this structure. Mallory drew on her knowledge of teaching from previous experiences during her undergraduate studies—both as a student and as a tutor. Mallory appreciated when her professors would guide her in developing her understanding of content rather than telling her the correct answer directly. Mallory also received training for a similar method of teaching for her tutor role:

> *We had a lot of training, in terms of how to tutor and, along with the coursework that I have, it makes me, generally, ask students questions, rather than give them answers or ask them to justify why something makes sense or not. If they call me over and they ask, "is this right?" I ask them, "what formulas can you use, what information are you given?"*

> *And I try to get them to make the connection themselves, rather than showing it to them directly.*

Accordingly, Mallory described her teaching style as "very question-based, generally. Just kind of going to people and asking them what they think." Our observations of Mallory were consistent with this statement; most of the sessions were centered around students' questions as they worked through the provided practice problems in small groups. For example, the scenario below occurred after a student asked Mallory to help their small group with one of the problems students were assigned:

> Student: *Can you help me with this one?*
>
> Mallory: *Okay. So I see you've written something down there—can you tell me what you've written down?*
>
> *[Student explanation]*
>
> Mallory: *Okay, that's a good start. Can you explain to me: what is physically going on in this kind of question?*

In this moment, Mallory drew on interactions with her students to grow her understanding of how to respond to students' questions with more questions. Mallory began to develop what Kelly[28] describes as tacit knowledge or knowledge that can only be created by teachers in their own context. This type of knowledge is rooted in teachers' professional activity and cannot be fully communicated.

**Consideration of students.** Mallory's teaching was also influenced by her knowledge of her students' interests and abilities. Mallory recognized that many of her students were not chemistry majors, which influenced Mallory's goal to help students learn transferable problem-solving skills. Additionally, Mallory evaluated her students through facial expressions, the questions they asked, and their scores on weekly quizzes. This information led her to categorize her students as "strong" or "weak." For example, Mallory said:

> *There tends to be the ones that I think of as weaker, they're weaker on every topic, like the kids who maybe their highest score on a quiz has been a five out of ten. Those are kids that to me, I would classify in the weaker category.*

Mallory's assessment of her students' understanding of course content influenced how Mallory interacted with different students. Mallory said, "I know who the weak students are, and I know who the strong students are, so I know how much prodding I generally need to give them." Mallory asked fewer prodding questions to students she perceived as doing well. This way, they had the space to work through more of the problem independently. Alternatively, for the students she saw struggling, she started with more basic questions and provided more guidance and direct answers as the students worked through the problem.

While Mallory would ideally allow all students to ask questions and help guide all students' in developing their understanding during the class session, she had to balance this goal with the structure set by the course professor:

> *I have to figure out how much I want to ask the students still because I still want them to participate, but I also know that the quiz is looming. I want to make sure they have ten minutes for the quiz and get through all of the questions.*

This challenge was exacerbated by the large number of students in her class, which made it even more difficult for her to answer all students' questions. In a post-observation interview from semester 1, Mallory said:

> *If [a student's] question is going to slow everything down, that's not going to be useful for everyone. And I'm supposed to be trying to really focus on the majority. So I both want to encourage the kids who are weakest to ask questions, but at the same time, when it's in front of the class at the board, I'm afraid of the questions that they're going to ask. When it's one on one with them at their seat? That's a perfect time for them to ask those kinds of questions.*

Over time, Mallory developed knowledge of what students typically struggle with and felt more prepared to teach her students with this knowledge. As a result, Mallory felt more confident teaching general chemistry discussions. In a post-observation interview from semester 2, Mallory said:

> *I'm less worried about it a little bit because I've taught it before. […] I know which ones are the hard problems; I know which ones are going to not take the students too much time in theory. Other than that, I mean, the main thing is that last term, I would show up like five minutes early for every class, and this term, I was showing up more like five minutes, like in the middle of the passing period for every class. […] I think that's a sign that I'm more comfortable with being in that position. Because I'm not like showing up early to like get everything set up. It's more like, "Okay, I need to go; I know what I need to do."*

**Reflection on teaching.** There were two occasions when Mallory explicitly reflected in post-observation interviews. The first was prompted by midterm student feedback, which is organized and implemented each semester by the chemistry department. The online anonymous feedback from Mallory's students prompted Mallory to set two goals: to improve her time management and to help students feel more comfortable asking questions in class. In an observation from semester 1, we observed Mallory make a slight change to the structure of the session by asking students if they had general questions about that week's content at the start of class. In her post-observation interview, she noted that asking students for questions as the start of class made the discussion session run more smoothly because she did not get asked the same questions from multiple groups of students during the groupwork portion of the session like she had previously in the semester. This change helped Mallory make progress towards both of her goals, as she was able to save time by only answering common questions once and she gave students time to ask any questions they may have. Mallory continued using this strategy in subsequent observations.

Additionally, toward the end of semester 1, Mallory explained that because she teaches multiple times a week, her experience from teaching her first session of the week informed future sessions. Mallory explained, "my Tuesday section is basically learning Wednesday's material a week behind. So I'll be like, Oh, I know, some common misconceptions or issues from that." Mallory learned what parts of each week's instruction are the most difficult for her students in the first class she teaches, then used this knowledge to adjust the way she approached the next session. This type of reflection—where the GTA uses their experience teaching one session to inform the next—was observed in all three participants' cases.

**Summary of Mallory's case.** Mallory discussed her teaching as being influenced by the course for which she taught. Within this structure, she aimed to ask students questions to guide their thinking, which was something she found helpful as a student and implemented as a tutor. Mallory categorized her students as having a strong or weak understanding of material, which influenced questions she asked her students. Mallory demonstrated relatively infrequent reflection on her teaching, but made noticeable changes based on this reflection. Otherwise, Mallory's teaching methods remained consistent throughout her first year of teaching.

### 4.6.2 Calvin

**Background.** Before moving to the US to start his Ph.D. program, Calvin received his BS chemistry degree in his home country, completed a master's program, and did one year of research. Calvin described his undergraduate experience as very formal: students came to class, took notes as the professor lectured, and there was limited interaction between instructors and students. As an undergraduate and master's student, Calvin tutored his peers. Calvin mentioned that this was more difficult than his experiences as a GTA because the content was more advanced, but it helped him prepare for his GTA role.

Calvin discussed the challenges he faced as a first-year international GTA, like learning a new language and experiencing jet lag as he adjusted to a nearly 12-hour time change. Calvin was also navigating a different academic culture that he perceived to be less formal than his prior experiences. Furthermore, Calvin noticed variations between how he learned chemistry and how chemistry is taught at this particular school. Calvin was concerned about being new to the school and country and said he did not want to mess up. Accordingly, Calvin had conversations with the course instructor to discuss course content and learn about the US education system. Calvin stated:

> *I'm quite new here. I don't want to mess up in any way because I know there are certain technicalities and differences from my education, what I have had in my undergrad, to what these people have here. That's the biggest concern. That I don't tell them something that confuses them in any way or anything because I should tell them that this is the way. Yes, if something seems different, I do talk it out with the host instructors. I tell them, "This is what I have learned. What I have learned, is it wrong or different, and how so?"*

Calvin's personal goals as a GTA were to gain experience teaching. He recognized that teaching helps his own understanding of the content, especially as he learns to anticipate students' questions:

> *I always have loved teaching, but... when you teach, what I found out, there are questions and things that, as a teacher, that person understands. Even the course instructors in a lot of places tell me, "Do ask questions. With your doubts, my concepts get clearer." There are some things I can [teach] and understand it better that way than for the $N^{th}$ time reading.*

At the start of graduate school, Calvin's career goals were to obtain a postdoc position after completing his Ph.D. This remained his goal throughout graduate school, and he was offered a postdoc position when we conducted our member checking.

**Course Structure.** Calvin taught two courses: organic chemistry I discussion and organic chemistry II lab. Organic chemistry I lecture is organized similarly to general chemistry lecture; it is typically taught by one course professor and two lecturers or postdoctoral fellows. About 1,300 students enroll in this course in the fall semester, and about eight GTAs are hired to teach one-hour discussion sections with 20-30 students each week. The organic chemistry I course professor provided little structure to Calvin's organic chemistry I discussion sessions. Unlike Mallory, Calvin could choose the content he reviewed and how he reviewed it in the classroom.

Organic chemistry II lab is taught by one course professor and one postdoctoral fellow. About 700 undergraduate students enroll in this course during the winter term, and 20-25 GTAs are hired to teach the lab sessions. Undergraduate students attend one one-hour weekly lecture where the course professor or postdoctoral fellow reviews the experiment for the week and relevant content. GTAs lead two four-hour labs with eighteen students in each section—students attend one lab session per week. When Calvin taught organic chemistry II lab, the sessions were heavily influenced by the experiments students needed to complete. The experiments often took the entire session to complete, and while Calvin had the freedom to introduce the experiment however he wanted to, students' tasks were dictated by the experimental protocol.

As a GTA, Calvin perceived his role to be someone who cleared up students' doubts about the chemistry content covered in the course they were enrolled in:

> *Since I'm in the discussion class, I try to solve or clear up the doubts that they have. Sometimes, if someone asks me a more advanced question than what is in the course, I give them an intro to it, but do tell them, "This is not something to be dealt right now." [...] Those are my particular goals since having the discussion class; I have to clear out their doubts. That's the mandatory and compulsory rule in it.*

Calvin mentioned this multiple times throughout his interviews. He stated that it is important to clear up students' doubts in discussions because they generally are unable to ask questions in their 300-400 student lecture classes. In a session that occurred before a course exam, Calvin organized his session as a review to help his students "accumulate the knowledge and keep it in one nice, sweet spot for the exam."

Over time, especially as Calvin shifted to teaching a lab course, he developed the goal of engaging his students. During an interview from semester 2, he said:

> *I wish I could do something to get them more motivated about it, rather than just doing it because it's a prerequisite for something. But yeah, I wish I could get them more interested in the chemistry because I'm teaching a chemistry lab. [...] I try learning how they think because that helps me to interact with them better.*

**Teaching strategies.** In the first semester of observations with Calvin, when he was teaching organic chemistry I discussion, we observed Calvin teaching in a lecture format. When asked how his undergraduate and master’s courses influenced the way he taught as a GTA, Calvin replied, “The course teacher matters a lot. That is who taught us. [...] We pick up certain traits that we like about how they taught us.” Calvin went on to say that he liked doing chalk talks (i.e., talking as he wrote on the chalkboard), starting with a problem, and reviewing key terms and phrases (e.g., resonance, pKa, etc.). While lecturing during his discussion sessions, Calvin liked to build foundational understanding:

> *I always like going back to basics. If you know your basics well, then it helps. [...] I guess I always take into account that the basics are everything. If you know that, then it helps you do the problem.*

Calvin’s second semester of observations was unique in that it was the only time we observed a GTA teaching a lab. Observation recordings mostly showed Calvin walking around the room to check in on students or sitting at the front while students work. Labs often started with students jumping right into work, and Calvin would give announcements and directions throughout the session.

Calvin seemed to prefer to work with small groups—he would make the same announcement multiple times to a few students at a time rather than announcing in front of the whole class at once. When walking around, Calvin would ask generally how students are doing and would give specific directions to certain groups of students. When he noticed students were really struggling, like the first time they did liquid-liquid extraction, Calvin completed that step of the protocol for the student. When sitting at the front, Calvin would watch his students work and sometimes give reminders (e.g., “don’t forget to do TLC.”). Whether Calvin was walking around or sitting down, students approached him to ask questions.

As Calvin gained experience teaching, he began discussing various real-life applications of chemistry to capture students’ attention during class. For example, in a session when the students were completing a Wittig reaction, Calvin shared information about Herbert C. Brown, who won the Nobel Prize in 1979 for the Wittig reaction. Calvin also had tangential conversations with his students, like talking about his responsibilities as a graduate student. Calvin discussed the organic chemistry I professor’s teaching as an influence on Calvin’s interactions with students:

> *I always loved what [the organic chemistry I professor] did, he was very interactive with the students, and that helps them. You know, people who are interested in this, they will always be interested. Unless you really make it dry and boring, they will be interested*

> *because they want to learn. But some of the people who have less interest for whatever reason, [the organic chemistry I professor] always had this charm, which makes [the students] interested. And it is a part of being interactive, more in a strange way. So that's what I've been trying to do, get them more interested in what they're doing. And tell them stories like this happened; this reaction got a Nobel Prize.*

Over the semester, Calvin's tangential conversations became more and more frequent. Although this was different from his experience as an undergraduate, which was very formal, Calvin found that these conversations helped students enjoy their time in the lab and thus influenced his goal of engaging students. During our member checking meeting, Calvin reflected on this development and said:

> *When I was teaching the second time, I got more used to talking with people on different topics. My education was in a culture which is way more formal. So I was not used to talking about like... pop culture and SpongeBob memes in class, but then the next time I was teaching that in Fall 2019, I could talk with people about those things and keep them engaged as they're doing the experiments. So that was one of the major things that was different.*

**Consideration of students.** As mentioned in the section above, Calvin discussed real-world topics related to the content students were learning to capture students' attention. Calvin discussed two factors that motivated this teaching style: the organic chemistry professor and his own knowledge of his students. Calvin noticed that most of his students were not interested in chemistry and were only taking organic chemistry II lab to fulfill graduation requirements:

> *Sadly speaking, [the students are] not that motivated nor interested. Because they have other interests, like pre-med, and that has an [organic chemistry II] lab pre requirement.*

In an interview during semester 2, Calvin further explained his motivation for this teaching strategy:

> *Sometimes we have to do stuff in life that they are not interested in, so I like to talk to them about different things. I know, like some of them went to a rock concert. And one of them was talking about how horrible the rock concert was, you know, so I fill in between talking to them, you know, so that they don't get bored in the lab. [...] It's always good to interact, get to know people. So I try to remember what their likings are, what they like to do. It gives me a start to converse with them. So I have progressed in this way.*

Calvin expanded his professional knowledge base by having conversations with students about topics outside of course content to keep students interested and enjoy their time in class.

When Calvin taught the organic chemistry II lab, his students recommended that he play music while they worked through the experiments. Based on Calvin's prior experiences working in a lab, he initially told the students he would not play music. However, after conversations with other GTAs and the graduate student mentor, who reassured Calvin that it was okay to play music and helped Calvin select music to play, Calvin allowed music in the lab.

> *[The students] were playing music in the lab. [...] From the culture I am in, they don't play music in the lab, like back in [my home country in my] undergrad days. But I realized people play music in the lab, because it's fine. They're just doing an experiment. They don't have to be very strict about it. It's not a lecture class.*

Calvin elaborated on the process that led him to allow music in lab:

> *Some of my students had started recommending me to do that since the start of the semester. And I said, like, "No, I'm not gonna let you do that because I might run into trouble." Then I saw a couple of my friends who are [GTAs] in other labs, they do that. So, I talked to the [graduate student mentor], and she said it's fine, that it's not against the rules. Then one [GTA] helped me because I don't have much of the things that they listen to.*

This change, prompted by conversations with students and peers, helped Calvin accomplish his goal of helping students enjoy their time in class.

**Reflection on teaching experiences.** Calvin reflected on his teaching in one of his post-observation interviews in semester 2. When Calvin taught organic chemistry II lab, he taught two sessions in one day, and we observed the second session. In this interview, Calvin described how his morning session informed his afternoon session:

> *I have two labs in one day. So I get the sort of the things that I'm not perfectly confident about or sure about, I do learn those things in the morning session from eight [AM] to twelve [PM]. [...] I saw that a lot of people cannot do the separating funnel. So then I realized I need to talk to everyone. In the eight to twelve session in the morning, I learn it, and in the next one, I do it better, because I know what instructions to give out to help them better and do it in an easier manner.*

Calvin discussed feeling more confident after he taught that session and learned what students typically struggle with.

During Calvin's member checking meeting, he reflected on how he adjusted his teaching based on midterm student feedback:

> *[Teaching] is like testing any hypothesis, right? Without any external bias, as you just said, or external mentoring. If you are internally motivated, you will want to run your hypothesis for some time. And so, for me, I tried it for a semester, then the next semester, I was like, 'Okay, this is my feedback. So, I need to change this based on the feedback that I got.' So yes, the feedback was from the students. And that is how I evolved. [...] Without a formal [GTA] training or mentoring. That is how I see being a [GTA] is like, right? [...] Trying out some crazy ideas or mentoring and teaching styles would be better, but I wasn't aware of if there are any resources like that. [...] A different resource would be helpful.*

Calvin described his feedback from students as an influence on his teacher learning and noted that he would have found additional resources helpful as well.

**Summary of Calvin's case.** Calvin had freedom during his first semester of teaching (organic chemistry I discussion) to lead his sessions however he wanted to. He chose to lecture, which seemed to be influenced by his experiences as an undergraduate in a formal education system. Calvin was inspired by the course professor's interesting lectures and aimed to keep students engaged by including intriguing real-world anecdotes about course content. While Calvin taught the lab session, there were few moments of instruction; Calvin mostly managed the session as students worked. Calvin reflected in just one of the interviews and, similar to Mallory, said that his experiences during his first session of the week influences how he taught his second session. Calvin had increasingly more frequent conversations with students about applications of course content, but otherwise, his teaching methods remained consistent.

### 4.6.3 Abby

**Background.** Abby started graduate school after completing her undergraduate education at an R1 institution. As an undergraduate student, Abby found it helpful that her professors were hands-on and set aside time to help students. They were available outside of class time—one even hosted a gathering at their home for their students. Within Abby's undergraduate courses, Abby found discussion sessions, during which students worked together with a GTA present, to be the most valuable for her learning. Additionally, Abby's mom was a middle-school English teacher. When Abby was growing up, she observed her mom teaching with different methods, including using games to incentivize students' class participation.

Abby had formal teaching experiences at her R1 undergraduate institution; she taught organic chemistry lab and a healthcare theater course, during which students act as patients for other students who plan to work in healthcare. Abby's healthcare theater and theater teaching positions were interactive in nature, which influenced Abby's teaching as a GTA:

> *Those classes are so different from a traditional science class because they are all interactive. So that has ...helped me shape how I want to... not just lecture in front of a class, but to build these interactive kinds of modules into things.*

Abby's personal goals as a GTA were to "try out different teaching techniques to be a better teacher in the future." At the start of graduate school, Abby said that she was interested in an industry job, even though she enjoyed teaching, before potentially becoming a professor. During our member checking meeting, Abby confirmed her plans to work in industry and said that after a few years of graduate school, she became less interested in being a professor in the future. When reflecting on how her career goals shifted, Abby explained:

> *I saw a lot of friends that were on the professorship track [...] kind of get into industry and are very satisfied with that lifestyle, and the pay, and everything. And I think it's a little bit harder once you leave academia to get back into academia as far as like, this style of ideas that you need to have and those kinds of things. [...] Now that I know a little bit more about what it means to do both of those kinds of things, it's definitely... industry is the path that I want to take.*

**Influence of course structure.** During Abby's first and third semesters of teaching, she taught discussions for a Fundamentals of Biochemistry course. One professor typically teaches this course, and about 120 students enroll. Three GTAs are hired to teach one-hour discussion sessions each week with about twenty students each. During Abby's first semester, there were a few instances when the course professor asked all GTAs to cover specific topics during their discussions. In observation 1, Abby lectured about the derivation of the Henderson-Hasselbalch equation, and in observation 2, Abby reviewed slides that the professor did not have time to review during lecture. In these instances, Abby first covered the content she was asked to cover and then taught the rest of the session however she chose. During the remaining observations in semester 1 and semester 3, Abby had the freedom to teach how she wanted.

During Abby's second semester of teaching, she taught discussion sections for an introductory bioinorganic chemistry course. The course is taught by one professor, and Abby was the only GTA. About 50 students enroll in this course. Similar to semesters 1 and 3, the course professor provided little structure to the discussion sections.

> *Having that back and forth with [the course professor], made me feel like I have more freedom to explore different teaching things within my section, whereas I think a lot of my peers come into a setup, you know, you're taking gen chem, you're teaching orgo that's been set for years, and you're given materials and it's a little bit more structure.*

As a GTA, Abby aimed to engage students by connecting with them and connecting chemistry to their personal lives. She wanted students to gain a love for the course material and to be prepared for their futures:

> *The number one thing I hope they gain is a love of the material and maybe some insights they didn't have coming into the course. And a lot of them are pre-med, so I'm hoping that they'll be prepared for their future using this course since it's a big part of the MCAT.*

**Teaching strategies.** To engage students in course material, Abby created games surrounding course content and played them with her students; eight out of our eleven observations of Abby involved some game. Abby attributes the origin of her teaching style to her experiences as an undergraduate and to observing her mom's teaching. Abby reflected on her experience with both good and bad teaching assistants while she was an undergraduate student:

> *I had some discussion sections that really worked, and the GTA did a really good job on how they structured their discussion sections versus some other discussion sections that were a little more open or a little too structured, that I found a lot of my peers were struggling with that format. So, I kind of tried to do a hybrid of what I learned in undergrad and then what I've taken from teaching those other kinds of courses like theater and healthcare theater, and try to kind of morph that into what I am doing now.*

Additionally, as Abby went through middle and high school, her mom learned about methods to gamify[40] her class to increase her students' engagement and motivation to learn. Abby's mom read books, implemented different games and reward systems, and altered her assessment practices to accomplish this goal. Observing her mom teach this way influenced the way Abby aimed to teach as a GTA:

> *As I was growing up, I saw [my mom] trying to incorporate those things (games). And then she was my teacher for several grades for me. So, then I got to see her implement those games with me. And so, seeing that, and hearing her teaching philosophy behind why she was trying to do those things, that's basically what inspired me and gave me the idea to do it in my classroom years later.*

In a session that occurred on October 31st, Abby created a "Halloween Obstacle Course." Students were arranged in groups of two or three, and each group started at a different station.

There were ten stations around the room, which matched the number of biochemistry questions students needed to answer. After each group answered the question that corresponded with the station they were at, the students checked their answer with Abby. If their answer was correct, they could play the game at their station (e.g., ring toss) to gain points for their group. Then, the group moved to the next station. When students checked their answers with Abby, she would ask students to verbalize their answers rather than reading them herself. Abby would then respond with follow-up questions to continue to gauge and scaffold student understanding. Abby's Halloween Obstacle Course was her own creation and although it required a lot of preparation time, Abby accomplished her goal of engaging students and said:

> *Every single one of them, they were smiling, laughing and calling me over and excited when they got an answer. You could tell that their level of enthusiasm was a little bit higher than when we're just going over straight up content, like in the normal style.*

Many of Abby's games followed a similar format where students needed to answer a question about course content before progressing in the game (e.g., moving their piece on the board game, gaining 'clues' to escape the 'escape room', or playing minigames to gain points for their team). The problems were more often chosen by Abby than by the course professor, and for each game, Abby intentionally chose a mix of more straightforward questions and questions that required more work and time. The few games that did not follow this format were designed to incorporate content into the actual game portion. For example, in an observation from semester 2, Abby's students were given pieces of paper with portions of a mechanism drawn on them. Abby's students then needed to arrange the pieces to complete the mechanism. This was the first time that Abby used a cooperative game—instead of a competitive one—where students had to work together to win rather than competing against each other or other groups. She mentioned that her lab mate introduced her to cooperative games and described how this influenced her planning:

> *I went in this week like, "How can I build a cooperative game instead of a competitive game," which is also a little bit difficult for me since I had never played that way. And I was worried. I wasn't sure how it was going to work out, there were a lot of trepidations going in, but the actual discussion couldn't have gone better.*

In sessions where Abby did not have a game planned, Abby reviewed example problems and provided time for students to raise any questions about course content.

**Consideration of students.** Abby considered her students in many different ways. Across all three observed semesters, Abby modified her plans for teaching based on a number of factors, including: the number of students present, whether the students recently had an exam or are preparing for an exam, and the questions students asked in the current session or previous sessions. For example, in an observation from semester 2, students had an exam coming up and Abby wanted to spend time reviewing content. To do this, Abby raised questions about topics that students in her other session had questions about, under the assumption that the students in the observed session would have similar questions. Abby also considered several factors related to student learning. Namely, she reflects on different modes of learning—kinesthetic, auditory, and visual—and how her activities support or do not support these different learning styles. She also thinks about the knowledge students have when they come into the discussion and that working in groups can help students learn. While Abby organizes students in groups during all three observed semesters, it was not until semester 3 when Abby reflects on the value of doing so during a post-observation interview:

> *I feel like collaboration is always like the better route to go, just because in both groups, there were basically two students that had learned this before and really had it under their belt. And the rest of them were kind of seeing this material for the first time. And so those students always had a different way than I would explain it. Since they learned it from a different class and so their peers benefited from getting a hands-on explanation in real time and figuring out things together. And they felt comfortable posing something to me like, "This is how we looked at it, is that the right way?" And getting guidance that way instead of just saying, "Is this right or wrong? Let's move to the next thing." So that was kind of cool. Versus the individualized [structure], they don't get to talk out their thought processes. I only get to see their end answer.*

Although Abby initially taught using games to engage students and motivate them to learn, throughout multiple semesters of using games, Abby recognized the value in having students collaborate with each other and learn the material together. She also reflected on how her smaller class size was beneficial for student learning. After we observed Abby modify one of her games because only two students attended her session, she said:

> *And when you're a small group, you get more vocalization from ones that aren't necessarily vocal all the time, especially when there's two of them, they almost have to talk, so I think that also gave them an opportunity to ask questions that maybe they wouldn't have if it was a larger group.*

**Reflection on teaching.** Abby frequently reflected on her teaching. Her reflection spanned across different time scales—within one class session, across different sessions in the same semester, and across different semesters. Within a single class session, Abby often adjusts her instruction based on formative assessments. For example, in a post-observation interview in semester 1, Abby described how she altered her teaching from what she had planned:

> *Since we were deriving that equation, the order of my problems would be related to that equation and variations of that equation. [...] But it didn't work out that way. I had it planned out, but then one of the students asked to go over a problem that was more related to what we just derived, so then I kind of flipped the order on what I was doing. [...] If they're not understanding something, they'll turn to each other and start to talk. And that's what they were doing during the derivation, so I stopped and tried to answer those questions.*

Within one semester, Abby often reflected on discussion sections that happened earlier in the week and other experiences with her students from earlier in the semester, similar to Mallory and Calvin. For instance, in a post-observation interview following during semester 1 she explained how her earlier session prepared her for the observed session:

> *This time in my morning discussion, there were two questions in there that, the way the book worded, left a lot up to interpretation. So I kind of had a heads up for that, because I had looked at those and then digested it with that group. So then when I got here, I kind of could circumvent that even before it happened.*

Because Abby taught the same course (biochemistry discussion) in both semesters 1 and 3, she used her experience in her first semester teaching to inform her third semester. During semester 3, Abby said:

> *I kept a binder basically and I broke down the weeks from last semester, a year ago when I did it. And so I would keep examples of the games that I did and I had a detailed outline of everything that I went through. And so then all I'm having to do this time is basically pull that out and then modify it slightly on timing and on track. And I also made notes of things I would've done differently last time. So then I modify it based off of my old notes too on it.*

Abby's reflection on her teaching across semesters provided her with an opportunity to make adjustments to her instruction.

**Summary of Abby's case.** Abby had freedom and felt more autonomy than Mallory and Calvin to teach how she wanted to during her discussions. She most often taught using games, which was a result of observing her mom learn to teach middle school English with games. Abby's use of games also accomplished her goal of engaging students. Abby often organized students in groups, and Abby later learned that this was beneficial for student learning. Abby reflected on and modified her teaching often but continued to use games as her teaching method.

### 4.7 Discussion

Guided by sociocultural theory of teacher learning, we explored our research questions by investigating the ways chemistry GTAs engage in teacher learning and how GTAs' teacher learning shifts as they gain experience within their social context. We utilized a case study approach in which we observed and interviewed three first-year chemistry GTAs multiple times over two or three semesters. We organized participants' cases by describing their background, course structure, teaching strategies, consideration of students, and reflection on teaching; each providing insight into their teaching learning.[28] Although all three participants were chemistry Ph.D. students who worked within the same department, they each had different experiences before graduate school and different experiences teaching in graduate school. Our case study presented herein describes the differences and similarities within and across participants to provide insight into GTAs' teacher learning within their unique social context.

As Kelly[28] states, teachers' identities "can be regarded as the ways in which practitioners see themselves in response to the actions of others towards them; that is, they are constantly changing outcomes of the interaction between how practitioners are constructed by others, and how they construct themselves, in and away from social situations" (p. 513).[28] This research contributes to existing research by focusing on GTAs' identities with a social lens, namely, how GTAs' social context and interactions may impact their identities. Our GTA participants' teacher identities were shaped by the course structure and professors' expectations of how the GTAs would fulfill their role. For instance, Mallory taught within a structure where the course professor had specific expectations, which included the content to cover and how to structure discussion sections. As such, Mallory viewed her role as someone to help students understand the content but balanced how she wanted to help students with the expectations placed on her by the course professors. Mallory felt that deviating from the recommended structure would be a great risk and thus taught with the same methods across the two observed semesters. In contrast, Abby felt a sense of autonomy when she taught her sessions. She worked more closely with the course professor, who did not have regular expectations for how Abby would teach her sessions. Abby implemented various self-created games to incentivize her students' participation and modified them throughout her teaching experience. The different structures in which Mallory and Abby taught influenced how they viewed their role and their level of autonomy, and thus their teacher identities.

Teacher identity is a key component of teacher learning, as the development of teacher identities supports the development of teacher knowledge through reflection on experiences.[28,41] Those whom GTAs engage with within their department influence their teacher identities.[8,42] There is a reciprocal relationship between identity and knowledge[41] as certain teacher identities may encourage the development of certain kinds of teaching knowledge as GTAs engage in their role. Thus, it is important to consider GTA teacher knowledge in light of their teacher identities.

Calvin, Mallory, and Abby's teacher knowledge about teaching methods and how they taught their students (their teaching practices) were largely based on their prior experiences as students or instructors. Several other studies have reported that GTAs draw on their prior experiences to inform their teaching[9,43] and can sometimes be problematic if the instructor is resistant to trying new teaching strategies.[44,45] As an undergraduate, Mallory found it helpful when her instructors encouraged her to think more deeply about content by replying to her questions with more questions. As a result, Mallory answered students' questions with more questions. Calvin gained teaching knowledge from his experiences as an undergraduate student and from observing the organic chemistry I course professor that lecturing is an effective way to teach chemistry. Accordingly, Calvin lectured during his discussion sessions. Abby was inspired by her mom's work as an English teacher to incorporate games to engage students in the content. We observed Abby employing self-created games to review content with her students and demonstrations to connect content to real life. GTAs consistently used these teaching strategies over the two or three semesters we observed, which echoes research on elementary science teachers who implement safe (i.e., comfortable) teaching strategies.[46] Appleton and Kindt[46] describe safe teaching strategies as manageable, reliable strategies that the teachers used in their schooling or during teacher preparation. Abby, for example, found that using games as an incentive for learning successfully engaged students during class and thus used this teaching strategy over all three semesters of teaching.

While participants' prior experiences strongly influenced their teaching, we also identified several factors that prompted slight changes in GTAs' teaching over time. All participants modified their teaching based on information they collected in the moment, their teacher knowing. The aspects of instructors' classrooms that they pay attention to may indicate what that instructor believes to be important to focus on. Reflections on these instances can influence instructors' actions in the classroom.[47] Mallory, Calvin, and Abby all reflected on their teaching when students struggled with particular content and used those reflections to inform their teaching in the future. Calvin shifted how he interacted with students to be more student-centered as he gained experience teaching.

Teacher reflection is an emphasized component of pre-service teacher programs, as it supports teacher learning and helps pre-service teachers shift their focus from themselves as teachers to their students as learners.[48,49] Although individual reflection supported GTAs' teacher learning, in all participants' cases, there was no mention of a structure present to support reflection outside of Mallory's mention of midterm student feedback implemented by the department. As a result, social interactions centered around teaching—a part of teaching practices[28]—were largely absent for our GTA participants. One instance was when Abby described a conversation with her lab mate, which prompted her to use a different type of game in her session. Furthermore, Calvin repeatedly expressed interest in learning how to teach more like the course professor, saying, "Somehow he does it, and I'm not very sure how he does it, but I would like to know more about it." Calvin ultimately did not find an opportunity to learn from this course professor other than by observing his lectures. While GTAs mentioned some peers or mentors who contributed to their practice, like graduate student mentors, there was no consistent, long-term structured community for GTAs, which could support teachers' development through meaningful collaboration and support.[50,51]

Although we have discussed the individual tenets of sociocultural theory of teacher learning for each participant, all tenets are interrelated.[28] Our participants' teaching stayed relatively consistent across their first year of teaching. When they modified their teaching, it was most often based on the GTAs' individual reflection of their own experiences on a lesson-by-lesson basis (e.g., changing their presentation of question based on experiences in an earlier session). Other studies suggest that support from colleagues enables some teachers to implement teaching strategies they may not otherwise attempt.[46,52] However, in comparison, chemistry GTAs teach in a relatively isolating and research-focused environment,[3] often with no training or discussion of evidence-based practices. This isolating environment may hinder GTAs' teacher identity development,[8] which may, in turn, prevent GTAs from seeking opportunities to develop their teaching knowledge.[9] This could result in GTAs relying solely on their content knowledge and their own experiences to inform their teaching. A two-day teacher training at the beginning of graduate school and weekly staff meetings focused on course logistics are not sufficient in supporting GTAs' teacher learning.[53] Rather, teacher learning requires "constant and iterative engagement in constructing and reconstructing professional knowledge using various perspectives" (pg. 509),[28] and such development is increased with increased collaboration. In a quote included in Calvin's case, he described learning to teach like testing a hypothesis. He tried out certain teaching methods, and then adjusted his teaching based on his experiences and feedback from students. He then mentioned that having additional resources would have been helpful to support his teaching.

When we expect GTAs to learn solely through isolated experience, we cannot necessarily expect to observe major developments in their teaching. Although many GTAs will work in academia and hold teaching positions in their futures,[5] opportunities to develop as instructors remain scarce in graduate school. Calvin, like GTAs in other studies,[3,8] was interested in participating in social structures to help improve his teaching. With the absence of collegial support and structures to prompt reflection, we cannot expect GTAs to significantly develop as instructors, although teaching as a GTA is often the only teaching experience faculty have before leading their own undergraduate courses.

## 4.8 Implications

Our results serve to inform future GTA training designs and departmental structures that may be useful to graduate students interested in careers in academia. Because many STEM GTAs will pursue careers involving teaching,[5] we make the following recommendations for teaching support alongside GTAs' research support. Our participants' teaching methods were often restricted to the methods they had experienced as students. Exposing GTAs to a set of evidence-based teaching strategies and providing low-risk opportunities for GTAs to try them out in their own context may encourage GTAs to go outside of their comfort zone and utilize different teaching strategies [54]. Further, for GTAs to develop their teaching knowledge and identities, they must have access to collegial support, which was rarely discussed in our interviews with participants.[8,46,52] Whether through a prolonged training or other structures, both peers and faculty could provide the mentorship and encouragement some GTAs need to develop their teaching knowledge and identities.[53] Teacher learning communities[50] or instructional coaching programs[51] can provide longer-term support for GTAs as they gain experience teaching and can create opportunities for GTAs to engage in social interactions centered around teaching.[28] Another key component to support GTA teacher learning is incorporating space for reflection on teaching experiences, which can also be accomplished through teacher learning communities and instructional coaching programs. Each of our participants adjusted their teaching based on internalizing experiences they had with students, and structuring and supporting this reflection may further assist GTAs in developing science teaching knowledge.[28,55,56] GTA teacher learning may be accelerated with more support to try new teaching methods and opportunities to reflect and learn from experiences.

This study aids in further expanding the sociocultural theory of teacher learning to encompass GTAs who teach in unique contexts. Through a case study involving observations and interviews with three chemistry GTAs, we have contributed to building theory of how GTAs teach and factors that inform their teaching. We also demonstrate what teacher learning looks like for teachers who are expected to learn independently and solely from their own experiences. As noted above, the structure provided by course professors laid a foundation for how GTAs could and could not teach their sessions, influencing their identities as teachers. Course requirements have been shown to play a role in GTAs' classroom discourse[22] and self-image.[12] Further research is needed to understand the impact of strict (i.e., Mallory's case) and lenient (i.e., Calvin and Abby's cases) structures on GTAs' teaching and how differing structures support teacher learning.

Additionally, many studies on GTAs' teaching knowledge have assumed that experienced GTAs will demonstrate more sophisticated teacher knowledge, in some cases, after only one semester of teaching.[21,24,57] However, other studies have described teachers with substantive teaching experience facing difficulties in implementing teaching methods that were new to them, like scaffolding during whole-class discussions[58] and teaching inquiry-oriented lessons.[59] Similarly, researchers have described experienced elementary science teachers going through a process of "re-novicing" as they adjust to teaching with the new Next Generation Science Standards.[60,61] The GTAs in this study appeared to only learn minimally while teaching for two or three semesters. The teacher learning that did occur primarily resulted in small adaptations to

GTAs' teaching. For example, Mallory learned that giving students space to ask general questions at the beginning of class helped her sessions run more smoothly. Thus, we should carefully consider assumptions that GTAs' teaching experience result in development of teaching knowledge or practices. This sentiment parallels recent work on in-service science teachers' teacher learning, which is considered to be dependent on their teaching context and individual needs, rather than their number of years of experience in the classroom.[62] Future work should deliberately focus on instructors with different levels of experience and identify their teaching expertise. Additionally, and in accordance with the national call to implement evidence-based teaching strategies in higher education,[14] future research should focus on instructors with expertise in evidence-based teaching strategies and identify the knowledge required to effectively implement such strategies in chemistry classes.[63,64] Such findings can subsequently inform the goals for instructor training throughout graduate school to support GTAs in their teacher learning and continued development as they take on faculty positions.

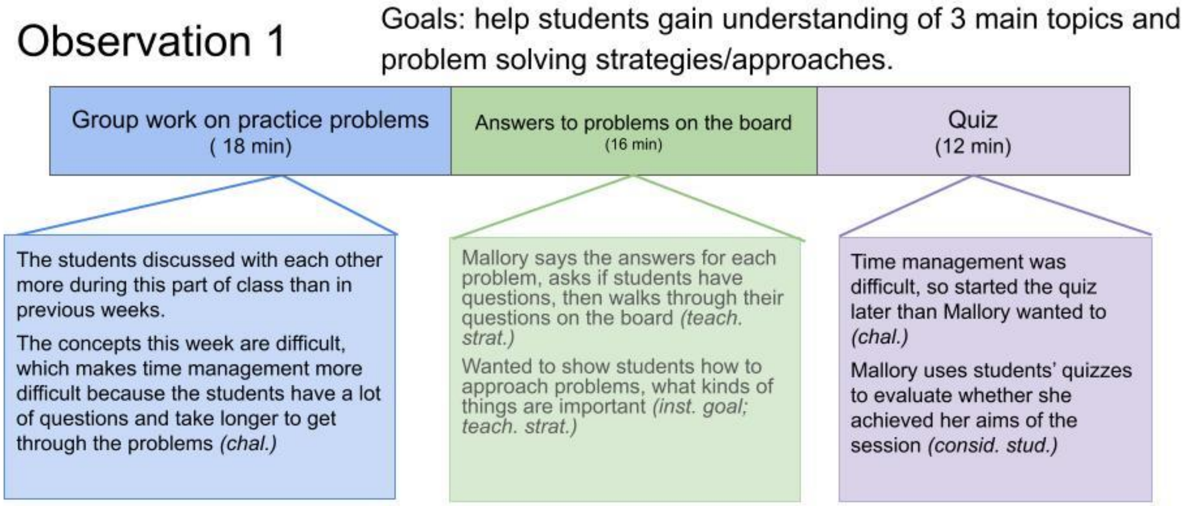
## 4.9 Supporting information

### 4.9.1 Post-observation interview protocol

How did your section go?
What material are you covering right now?
What were the aims of your particular section?
What were the goals besides covering the content?
    Did you achieve your goals?
What parts of your section could have gone better?
What parts of your section went particularly well?
    How can you tell?
Have you taught this content before?
Did you use any teaching techniques that you haven't used before?
Were there challenges with using these new techniques?
What went better than the previous week?
What do you feel like you could improve on for next week?

### 4.9.2 Observation summaries: Mallory

Semester 1: General chemistry discussion



Goals: help students gain understanding of 3 main topics and problem solving strategies/approaches.

The students discussed with each other more during this part of class than in previous weeks.

The concepts this week are difficult, which makes time management more difficult because the students have a lot of questions and take longer to get through the problems *(chal.)*

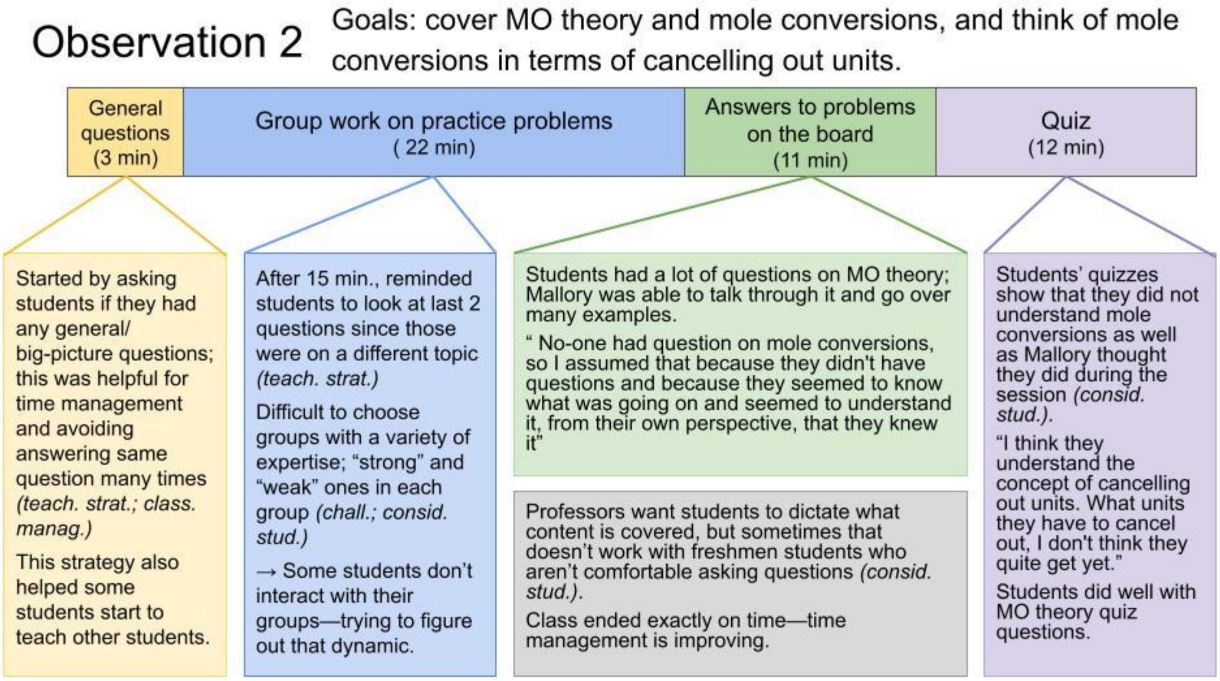
Mallory says the answers for each problem, asks if students have questions, then walks through their questions on the board *(teach. strat.)*

Wanted to show students how to approach problems, what kinds of things are important *(inst. goal; teach. strat.)*

Time management was difficult, so started the quiz later than Mallory wanted to *(chal.)*

Mallory uses students' quizzes to evaluate whether she achieved her aims of the session *(consid. stud.)*

**Figure 4.2a.** Mallory's observation summaries: observation 1.



Goals: cover MO theory and mole conversions, and think of mole conversions in terms of cancelling out units.

Started by asking students if they had any general/ big-picture questions; this was helpful for time management and avoiding answering same question many times *(teach. strat.; class. manag.)*

This strategy also helped some students start to teach other students.

After 15 min., reminded students to look at last 2 questions since those were on a different topic *(teach. strat.)*

Difficult to choose groups with a variety of expertise; "strong" and "weak" ones in each group *(chall.; consid. stud.)*

→ Some students don't interact with their groups—trying to figure out that dynamic.

Students had a lot of questions on MO theory; Mallory was able to talk through it and go over many examples.

" No-one had question on mole conversions, so I assumed that because they didn't have questions and because they seemed to know what was going on and seemed to understand it, from their own perspective, that they knew it"

Professors want students to dictate what content is covered, but sometimes that doesn't work with freshmen students who aren't comfortable asking questions *(consid. stud.)*.

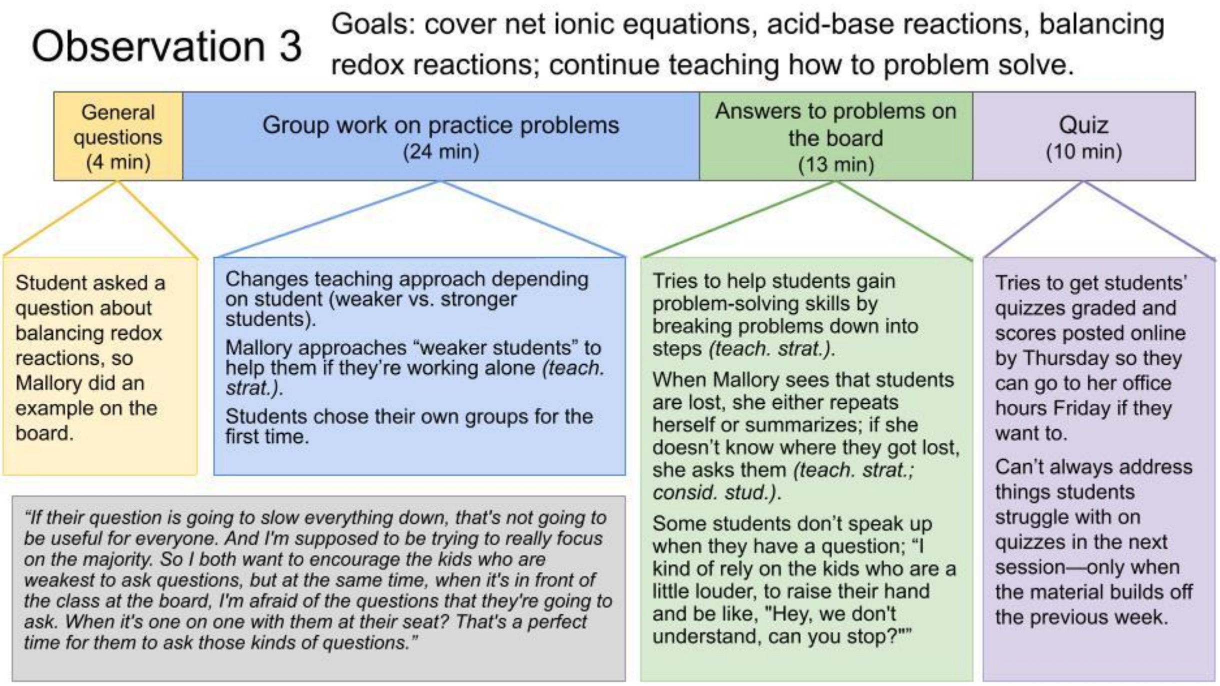
Class ended exactly on time—time management is improving.

Students' quizzes show that they did not understand mole conversions as well as Mallory thought they did during the session *(consid. stud.)*.

"I think they understand the concept of cancelling out units. What units they have to cancel out, I don't think they quite get yet."

Students did well with MO theory quiz questions.

**Figure 4.2b.** Mallory's observation summaries: observation 2.



Observation 3

Goals: cover net ionic equations, acid-base reactions, balancing redox reactions; continue teaching how to problem solve.

General questions (4 min)

Group work on practice problems (24 min)

Answers to problems on the board (13 min)

Quiz (10 min)

Student asked a question about balancing redox reactions, so Mallory did an example on the board.

Changes teaching approach depending on student (weaker vs. stronger students).

Mallory approaches "weaker students" to help them if they're working alone *(teach. strat.)*.

Students chose their own groups for the first time.

*"If their question is going to slow everything down, that's not going to be useful for everyone. And I'm supposed to be trying to really focus on the majority. So I both want to encourage the kids who are weakest to ask questions, but at the same time, when it's in front of the class at the board, I'm afraid of the questions that they're going to ask. When it's one on one with them at their seat? That's a perfect time for them to ask those kinds of questions."*

Tries to help students gain problem-solving skills by breaking problems down into steps *(teach. strat.)*.

When Mallory sees that students are lost, she either repeats herself or summarizes; if she doesn't know where they got lost, she asks them *(teach. strat.; consid. stud.)*.

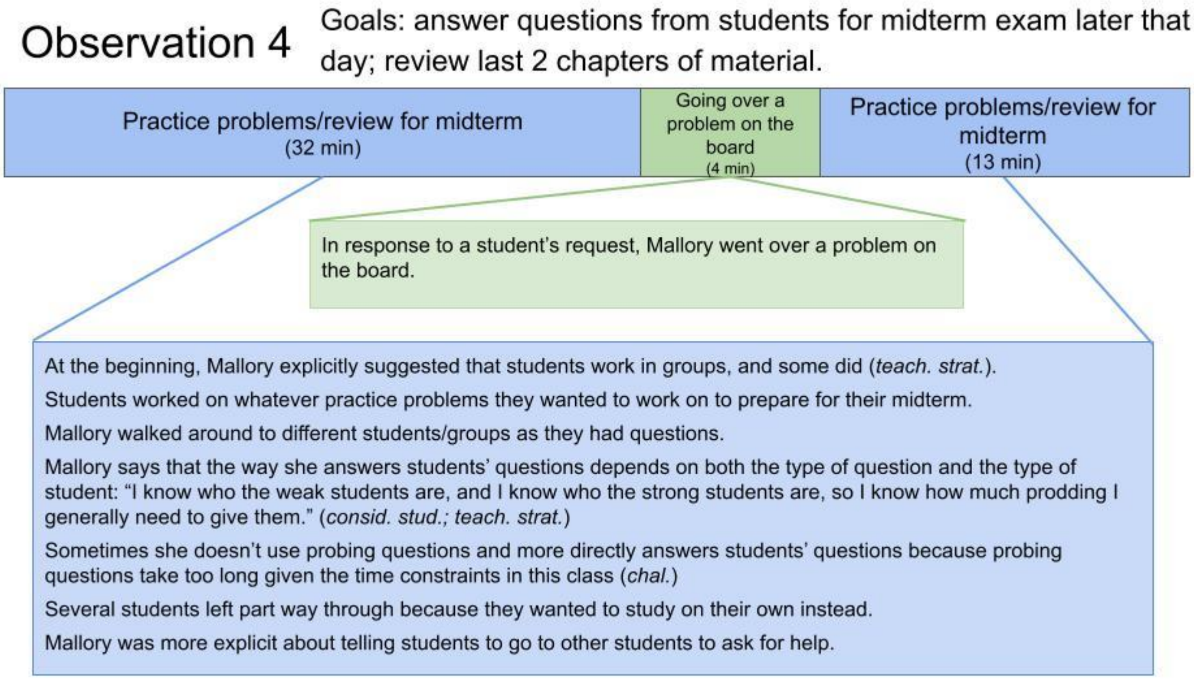
Some students don't speak up when they have a question; "I kind of rely on the kids who are a little louder, to raise their hand and be like, "Hey, we don't understand, can you stop?""

Tries to get students' quizzes graded and scores posted online by Thursday so they can go to her office hours Friday if they want to.

Can't always address things students struggle with on quizzes in the next session—only when the material builds off the previous week.

**Figure 4.2c.** Mallory's observation summaries: observation 3.

## Semester 2: General chemistry discussion



Observation 4

Goals: answer questions from students for midterm exam later that day; review last 2 chapters of material.

Practice problems/review for midterm (32 min)

Going over a problem on the board (4 min)

Practice problems/review for midterm (13 min)

In response to a student's request, Mallory went over a problem on the board.

At the beginning, Mallory explicitly suggested that students work in groups, and some did (*teach. strat.*).

Students worked on whatever practice problems they wanted to work on to prepare for their midterm.

Mallory walked around to different students/groups as they had questions.

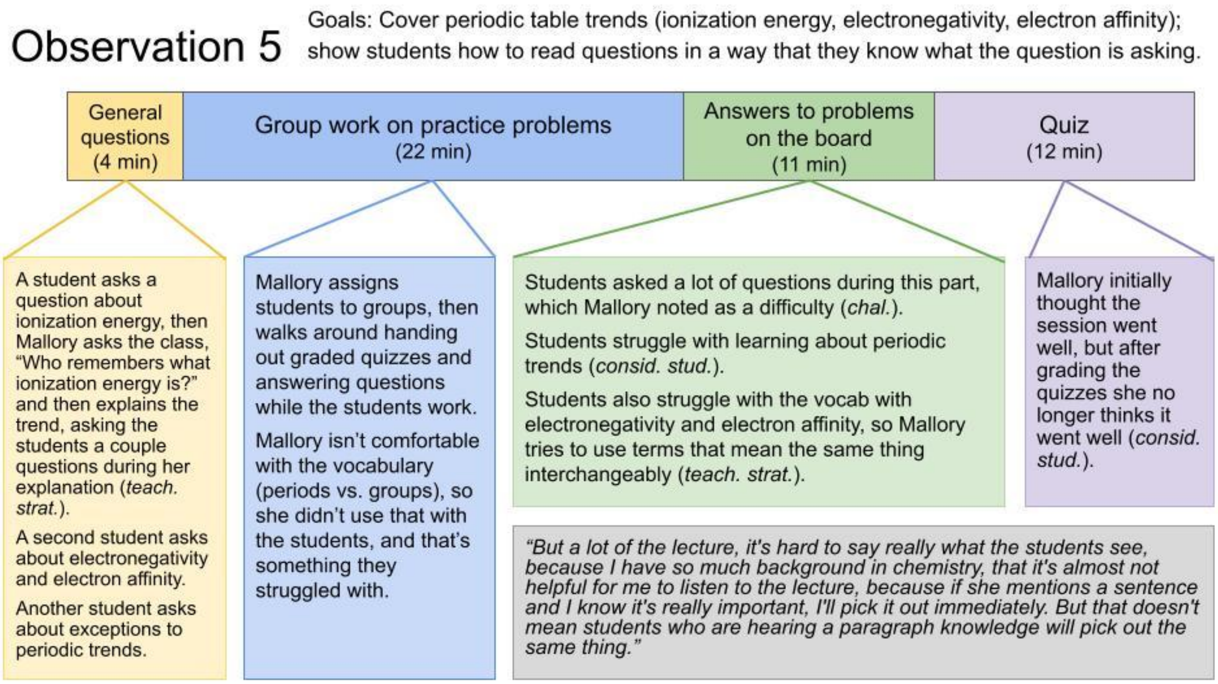
Mallory says that the way she answers students' questions depends on both the type of question and the type of student: "I know who the weak students are, and I know who the strong students are, so I know how much prodding I generally need to give them." (*consid. stud.; teach. strat.*)

Sometimes she doesn't use probing questions and more directly answers students' questions because probing questions take too long given the time constraints in this class (*chal.*)

Several students left part way through because they wanted to study on their own instead.

Mallory was more explicit about telling students to go to other students to ask for help.

**Figure 4.2d.** Mallory's observation summaries: observation 4.



Observation 5

Goals: Cover periodic table trends (ionization energy, electronegativity, electron affinity); show students how to read questions in a way that they know what the question is asking.

General questions (4 min)

Group work on practice problems (22 min)

Answers to problems on the board (11 min)

Quiz (12 min)

A student asks a question about ionization energy, then Mallory asks the class, “Who remembers what ionization energy is?” and then explains the trend, asking the students a couple questions during her explanation (*teach. strat.*).

A second student asks about electronegativity and electron affinity.

Another student asks about exceptions to periodic trends.

Mallory assigns students to groups, then walks around handing out graded quizzes and answering questions while the students work.

Mallory isn’t comfortable with the vocabulary (periods vs. groups), so she didn’t use that with the students, and that’s something they struggled with.

Students asked a lot of questions during this part, which Mallory noted as a difficulty (*chal.*).

Students struggle with learning about periodic trends (*consid. stud.*).

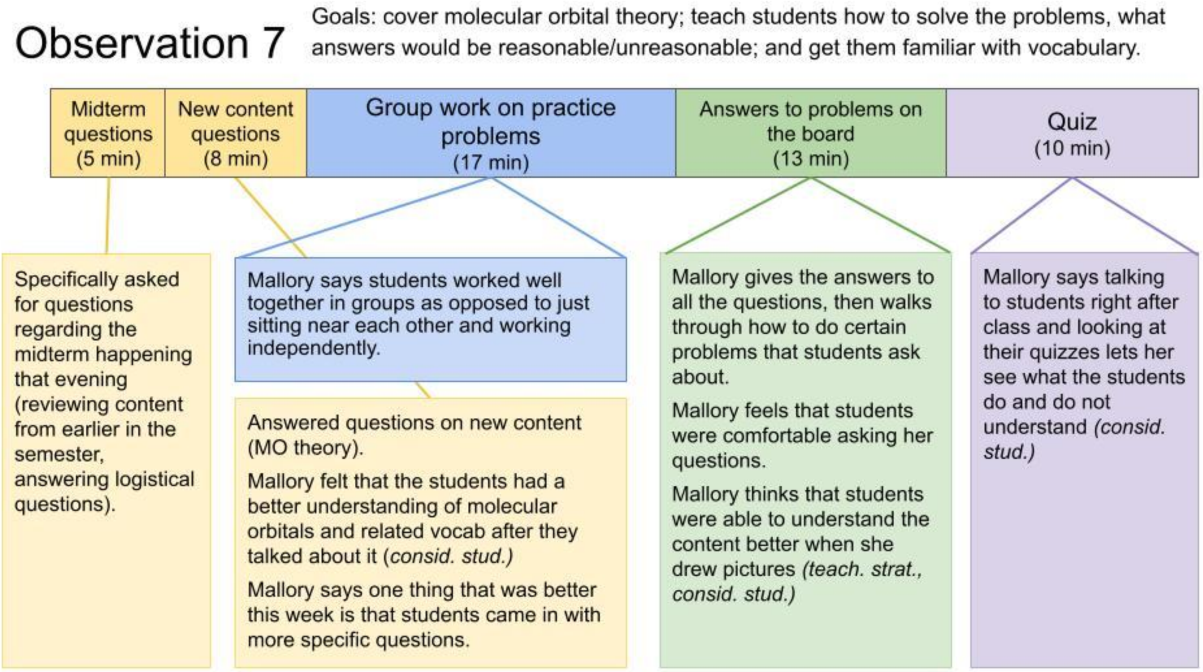
Students also struggle with the vocab with electronegativity and electron affinity, so Mallory tries to use terms that mean the same thing interchangeably (*teach. strat.*).

Mallory initially thought the session went well, but after grading the quizzes she no longer thinks it went well (*consid. stud.*).

*“But a lot of the lecture, it's hard to say really what the students see, because I have so much background in chemistry, that it's almost not helpful for me to listen to the lecture, because if she mentions a sentence and I know it's really important, I'll pick it out immediately. But that doesn't mean students who are hearing a paragraph knowledge will pick out the same thing.”*

**Figure 4.2e.** Mallory’s observation summaries: observation 5.

Observation 6 was not analyzed due to technical complications.



Observation 7

Goals: cover molecular orbital theory; teach students how to solve the problems, what answers would be reasonable/unreasonable; and get them familiar with vocabulary.

Midterm questions (5 min)

New content questions (8 min)

Group work on practice problems (17 min)

Answers to problems on the board (13 min)

Quiz (10 min)

Specifically asked for questions regarding the midterm happening that evening (reviewing content from earlier in the semester, answering logistical questions).

Mallory says students worked well together in groups as opposed to just sitting near each other and working independently.

Answered questions on new content (MO theory).

Mallory felt that the students had a better understanding of molecular orbitals and related vocab after they talked about it (*consid. stud.)*

Mallory says one thing that was better this week is that students came in with more specific questions.

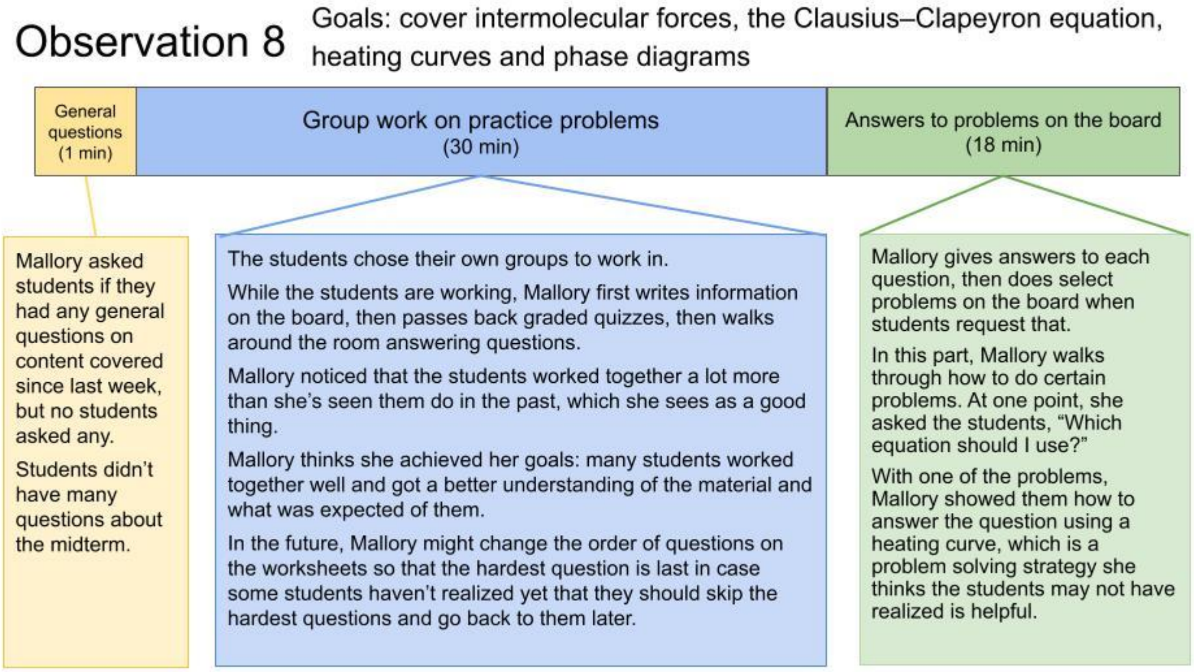
Mallory gives the answers to all the questions, then walks through how to do certain problems that students ask about.

Mallory feels that students were comfortable asking her questions.

Mallory thinks that students were able to understand the content better when she drew pictures *(teach. strat., consid. stud.)*

Mallory says talking to students right after class and looking at their quizzes lets her see what the students do and do not understand *(consid. stud.)*

**Figure 4.2f.** Mallory’s observation summaries: observation 7.



Observation 8

Goals: cover intermolecular forces, the Clausius–Clapeyron equation, heating curves and phase diagrams

General questions (1 min)

Group work on practice problems (30 min)

Answers to problems on the board (18 min)

Mallory asked students if they had any general questions on content covered since last week, but no students asked any.

Students didn't have many questions about the midterm.

The students chose their own groups to work in.

While the students are working, Mallory first writes information on the board, then passes back graded quizzes, then walks around the room answering questions.

Mallory noticed that the students worked together a lot more than she's seen them do in the past, which she sees as a good thing.

Mallory thinks she achieved her goals: many students worked together well and got a better understanding of the material and what was expected of them.

In the future, Mallory might change the order of questions on the worksheets so that the hardest question is last in case some students haven't realized yet that they should skip the hardest questions and go back to them later.

Mallory gives answers to each question, then does select problems on the board when students request that.

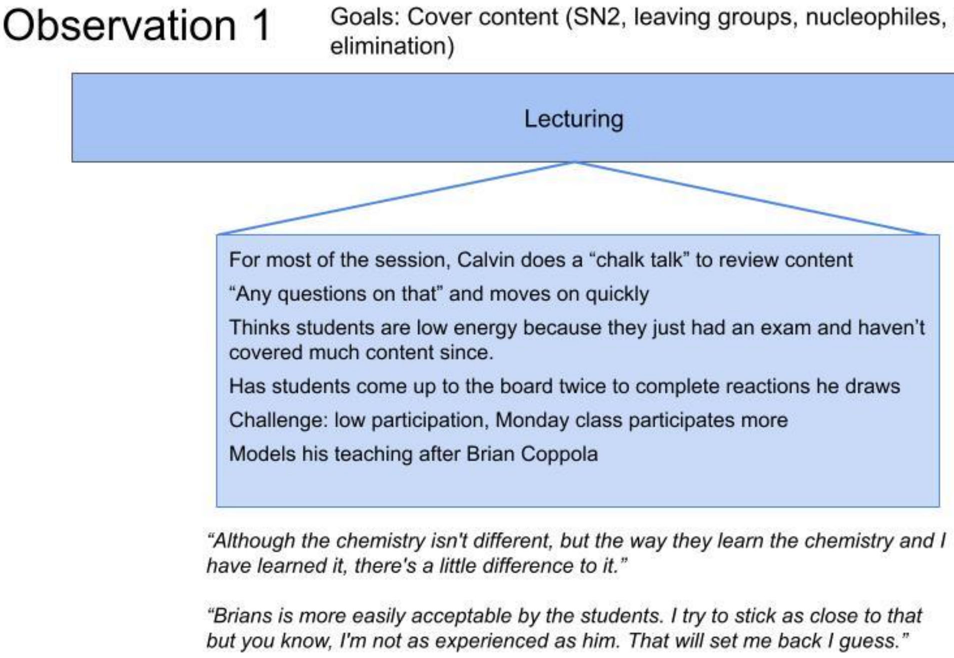
In this part, Mallory walks through how to do certain problems. At one point, she asked the students, "Which equation should I use?"

With one of the problems, Mallory showed them how to answer the question using a heating curve, which is a problem solving strategy she thinks the students may not have realized is helpful.

**Figure 4.2g.** Mallory's observation summaries: observation 8.

### 4.9.3 Observation Summaries: Calvin

Semester 1: Organic chemistry I discussion



Observation 1

Goals: Cover content (SN2, leaving groups, nucleophiles, briefly talk about elimination)

Lecturing

For most of the session, Calvin does a "chalk talk" to review content

"Any questions on that" and moves on quickly

Thinks students are low energy because they just had an exam and haven't covered much content since.

Has students come up to the board twice to complete reactions he draws

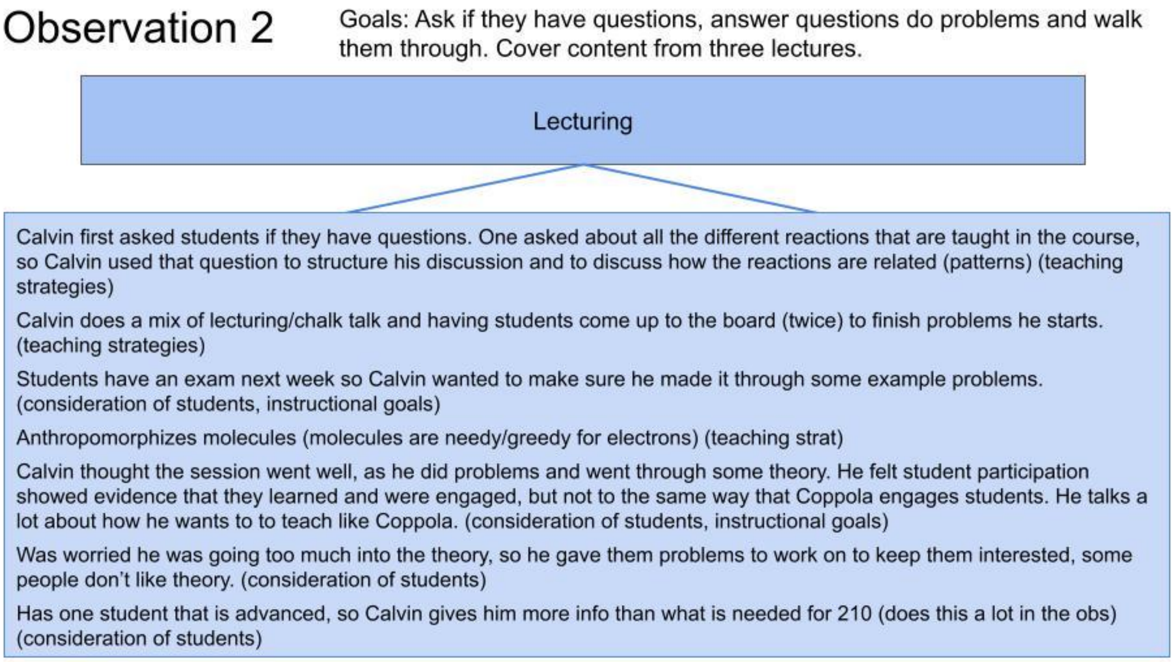
Challenge: low participation, Monday class participates more

Models his teaching after Brian Coppola

*"Although the chemistry isn't different, but the way they learn the chemistry and I have learned it, there's a little difference to it."*

*"Brians is more easily acceptable by the students. I try to stick as close to that but you know, I'm not as experienced as him. That will set me back I guess."*

**Figure 4.3a.** Calvin's observation summaries: observation 1.



Observation 2

Goals: Ask if they have questions, answer questions do problems and walk them through. Cover content from three lectures.

Lecturing

Calvin first asked students if they have questions. One asked about all the different reactions that are taught in the course, so Calvin used that question to structure his discussion and to discuss how the reactions are related (patterns) (teaching strategies)

Calvin does a mix of lecturing/chalk talk and having students come up to the board (twice) to finish problems he starts. (teaching strategies)

Students have an exam next week so Calvin wanted to make sure he made it through some example problems. (consideration of students, instructional goals)

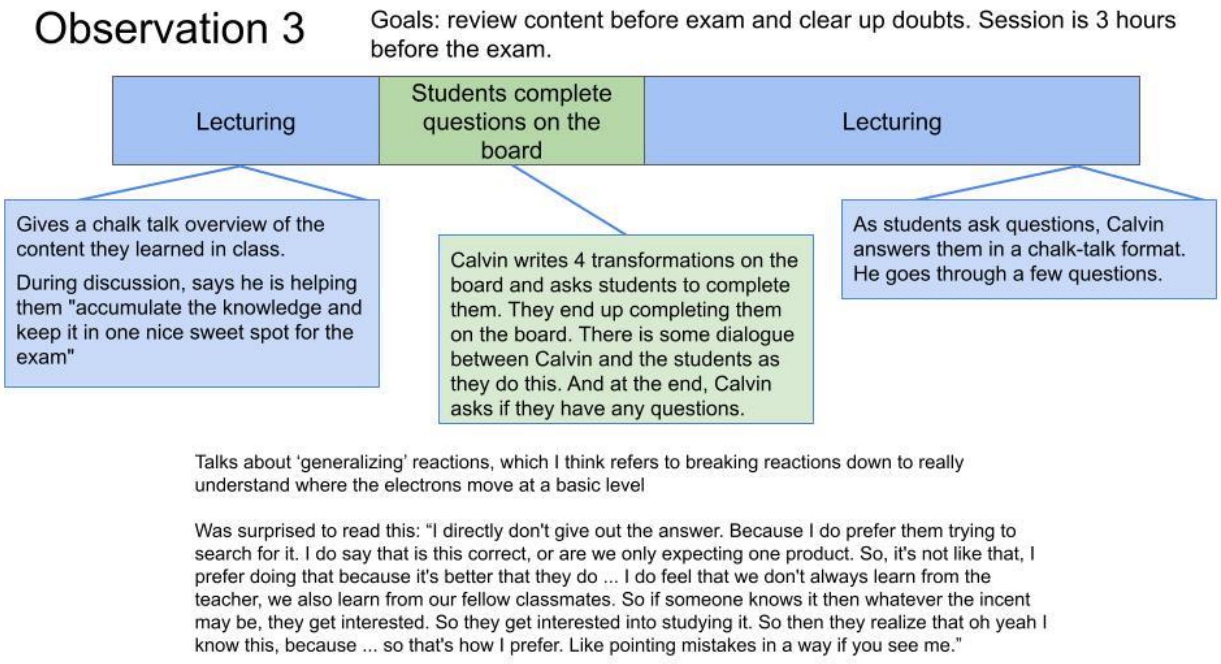
Anthropomorphizes molecules (molecules are needy/greedy for electrons) (teaching strat)

Calvin thought the session went well, as he did problems and went through some theory. He felt student participation showed evidence that they learned and were engaged, but not to the same way that Coppola engages students. He talks a lot about how he wants to to teach like Coppola. (consideration of students, instructional goals)

Was worried he was going too much into the theory, so he gave them problems to work on to keep them interested, some people don't like theory. (consideration of students)

Has one student that is advanced, so Calvin gives him more info than what is needed for 210 (does this a lot in the obs) (consideration of students)

**Figure 4.3b.** Calvin's observation summaries: observation 2.



Observation 3

Goals: review content before exam and clear up doubts. Session is 3 hours before the exam.

Lecturing | Students complete questions on the board | Lecturing

Gives a chalk talk overview of the content they learned in class.

During discussion, says he is helping them "accumulate the knowledge and keep it in one nice sweet spot for the exam"

Calvin writes 4 transformations on the board and asks students to complete them. They end up completing them on the board. There is some dialogue between Calvin and the students as they do this. And at the end, Calvin asks if they have any questions.

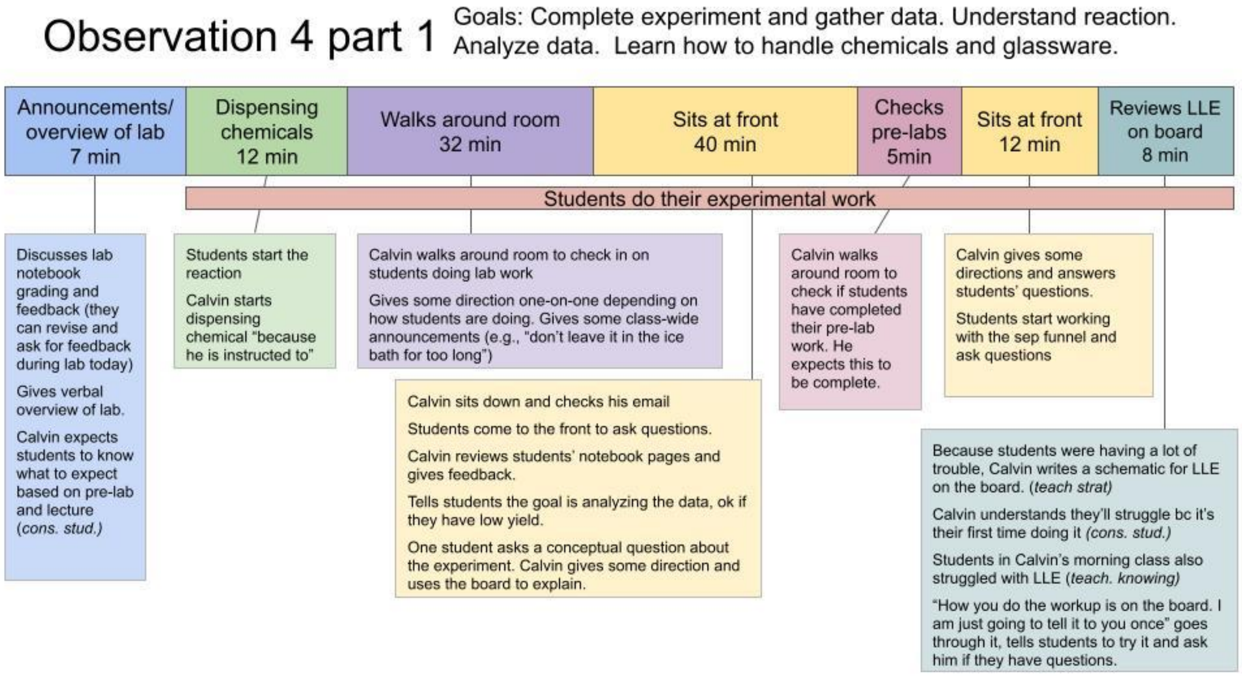
As students ask questions, Calvin answers them in a chalk-talk format. He goes through a few questions.

Talks about 'generalizing' reactions, which I think refers to breaking reactions down to really understand where the electrons move at a basic level

Was surprised to read this: "I directly don't give out the answer. Because I do prefer them trying to search for it. I do say that is this correct, or are we only expecting one product. So, it's not like that, I prefer doing that because it's better that they do ... I do feel that we don't always learn from the teacher, we also learn from our fellow classmates. So if someone knows it then whatever the incent may be, they get interested. So they get interested into studying it. So then they realize that oh yeah I know this, because ... so that's how I prefer. Like pointing mistakes in a way if you see me."

**Figure 4.3c.** Calvin's observation summaries: observation 3.

Semester 2: Organic chemistry II lab



Observation 4 part 1

Goals: Complete experiment and gather data. Understand reaction. Analyze data. Learn how to handle chemicals and glassware.

Announcements/ overview of lab 7 min

Dispensing chemicals 12 min

Walks around room 32 min

Sits at front 40 min

Checks pre-labs 5min

Sits at front 12 min

Reviews LLE on board 8 min

Students do their experimental work

Discusses lab notebook grading and feedback (they can revise and ask for feedback during lab today)

Gives verbal overview of lab.

Calvin expects students to know what to expect based on pre-lab and lecture (*cons. stud.*)

Students start the reaction

Calvin starts dispensing chemical "because he is instructed to"

Calvin walks around room to check in on students doing lab work

Gives some direction one-on-one depending on how students are doing. Gives some class-wide announcements (e.g., "don't leave it in the ice bath for too long")

Calvin sits down and checks his email

Students come to the front to ask questions.

Calvin reviews students' notebook pages and gives feedback.

Tells students the goal is analyzing the data, ok if they have low yield.

One student asks a conceptual question about the experiment. Calvin gives some direction and uses the board to explain.

Calvin walks around room to check if students have completed their pre-lab work. He expects this to be complete.

Calvin gives some directions and answers students' questions.

Students start working with the sep funnel and ask questions

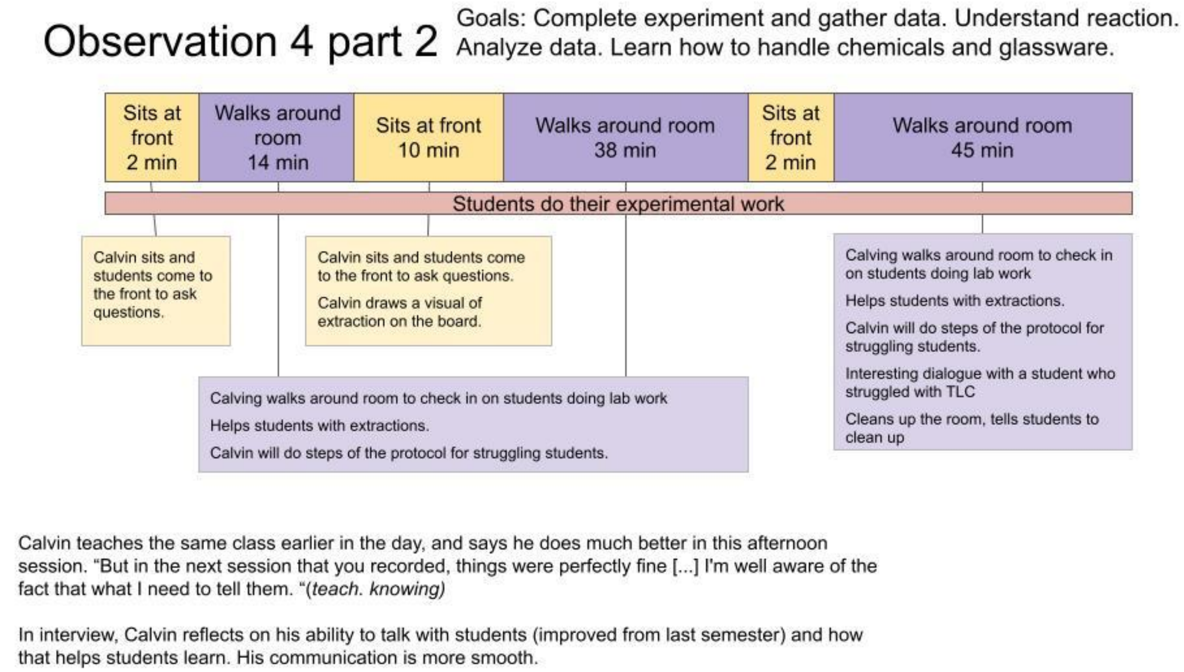
Because students were having a lot of trouble, Calvin writes a schematic for LLE on the board. (*teach strat)*

Calvin understands they'll struggle bc it's their first time doing it *(cons. stud.)*

Students in Calvin's morning class also struggled with LLE (*teach. knowing)*

"How you do the workup is on the board. I am just going to tell it to you once" goes through it, tells students to try it and ask him if they have questions.

**Figure 4.3d.** Calvin's observation summaries: observation 4 part 1.



Observation 4 part 2

Goals: Complete experiment and gather data. Understand reaction. Analyze data. Learn how to handle chemicals and glassware.

Sits at front 2 min

Walks around room 14 min

Sits at front 10 min

Walks around room 38 min

Sits at front 2 min

Walks around room 45 min

Students do their experimental work

Calvin sits and students come to the front to ask questions.

Calvin sits and students come to the front to ask questions.

Calvin draws a visual of extraction on the board.

Calving walks around room to check in on students doing lab work

Helps students with extractions.

Calvin will do steps of the protocol for struggling students.

Calving walks around room to check in on students doing lab work

Helps students with extractions.

Calvin will do steps of the protocol for struggling students.

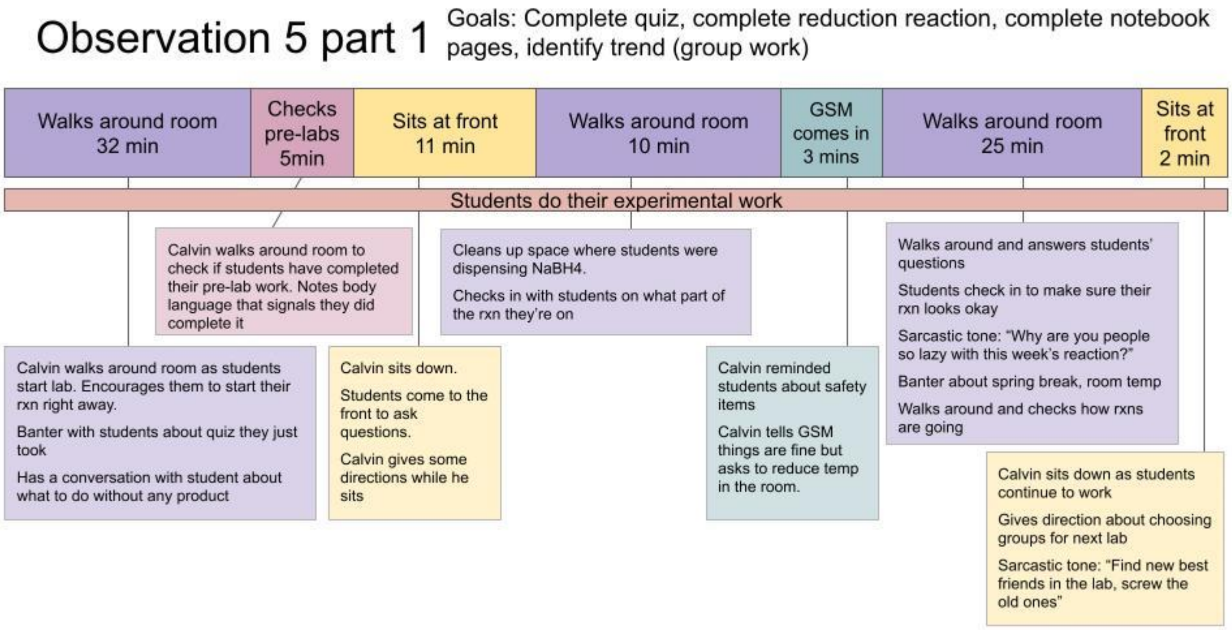
Interesting dialogue with a student who struggled with TLC

Cleans up the room, tells students to clean up

Calvin teaches the same class earlier in the day, and says he does much better in this afternoon session. "But in the next session that you recorded, things were perfectly fine [...] I'm well aware of the fact that what I need to tell them. "(*teach. knowing)*

In interview, Calvin reflects on his ability to talk with students (improved from last semester) and how that helps students learn. His communication is more smooth.

**Figure 4.3e.** Calvin's observation summaries: observation 4 part 2.



Goals: Complete quiz, complete reduction reaction, complete notebook pages, identify trend (group work)

Calvin walks around room as students start lab. Encourages them to start their rxn right away.

Banter with students about quiz they just took

Has a conversation with student about what to do without any product

Calvin walks around room to check if students have completed their pre-lab work. Notes body language that signals they did complete it

Calvin sits down.

Students come to the front to ask questions.

Calvin gives some directions while he sits

Cleans up space where students were dispensing NaBH4.

Checks in with students on what part of the rxn they're on

Calvin reminded students about safety items

Calvin tells GSM things are fine but asks to reduce temp in the room.

Walks around and answers students' questions

Students check in to make sure their rxn looks okay

Sarcastic tone: "Why are you people so lazy with this week's reaction?"

Banter about spring break, room temp

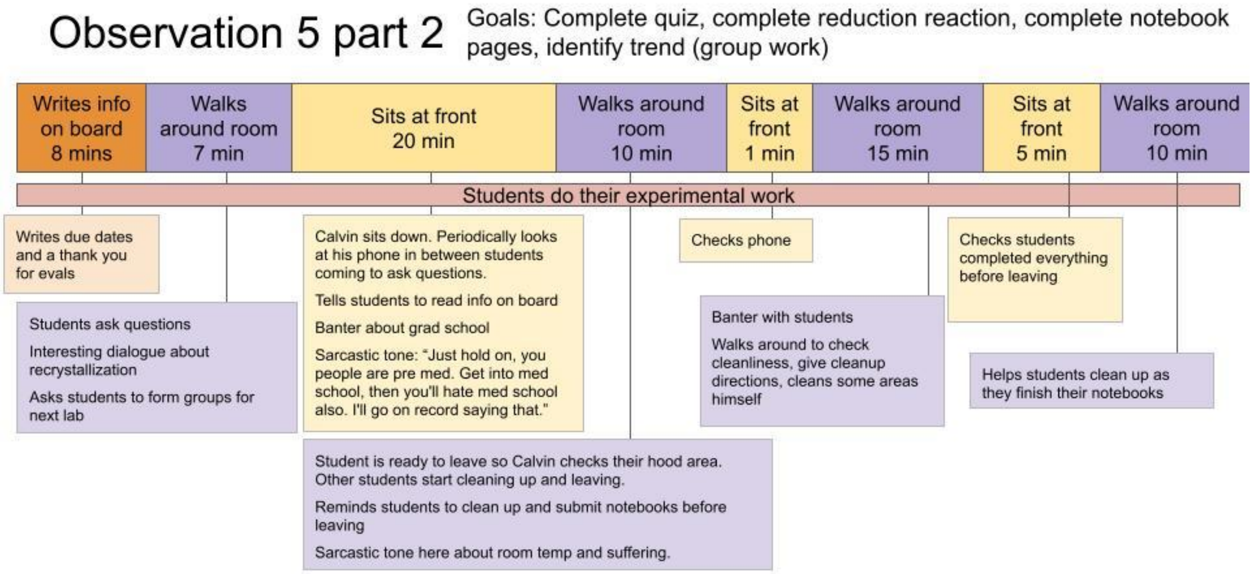
Walks around and checks how rxns are going

Calvin sits down as students continue to work

Gives direction about choosing groups for next lab

Sarcastic tone: "Find new best friends in the lab, screw the old ones"

**Figure 4.3f.** Calvin's observation summaries: observation 5 part 1.



Goals: Complete quiz, complete reduction reaction, complete notebook pages, identify trend (group work)

Writes due dates and a thank you for evals

Students ask questions

Interesting dialogue about recrystallization

Asks students to form groups for next lab

Calvin sits down. Periodically looks at his phone in between students coming to ask questions.

Tells students to read info on board

Banter about grad school

Sarcastic tone: "Just hold on, you people are pre med. Get into med school, then you'll hate med school also. I'll go on record saying that."

Student is ready to leave so Calvin checks their hood area. Other students start cleaning up and leaving.

Reminds students to clean up and submit notebooks before leaving

Sarcastic tone here about room temp and suffering.

Checks phone

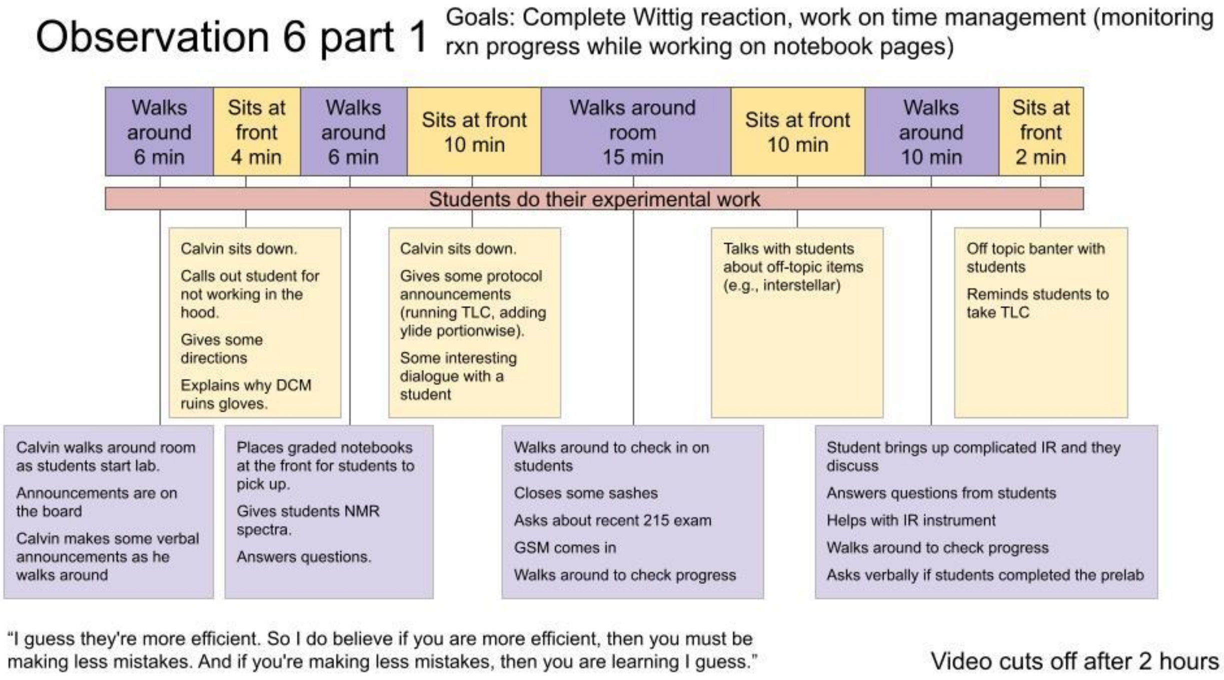
Banter with students

Walks around to check cleanliness, give cleanup directions, cleans some areas himself

Checks students completed everything before leaving

Helps students clean up as they finish their notebooks

**Figure 4.3g.** Calvin's observation summaries: observation 5 part 2.



Calvin sits down.

Calls out student for not working in the hood.

Gives some directions

Explains why DCM ruins gloves.

Calvin sits down.

Gives some protocol announcements (running TLC, adding ylide portionwise).

Some interesting dialogue with a student

Talks with students about off-topic items (e.g., interstellar)

Off topic banter with students

Reminds students to take TLC

Calvin walks around room as students start lab.

Announcements are on the board

Calvin makes some verbal announcements as he walks around

Places graded notebooks at the front for students to pick up.

Gives students NMR spectra.

Answers questions.

Walks around to check in on students

Closes some sashes

Asks about recent 215 exam

GSM comes in

Walks around to check progress

Student brings up complicated IR and they discuss

Answers questions from students

Helps with IR instrument

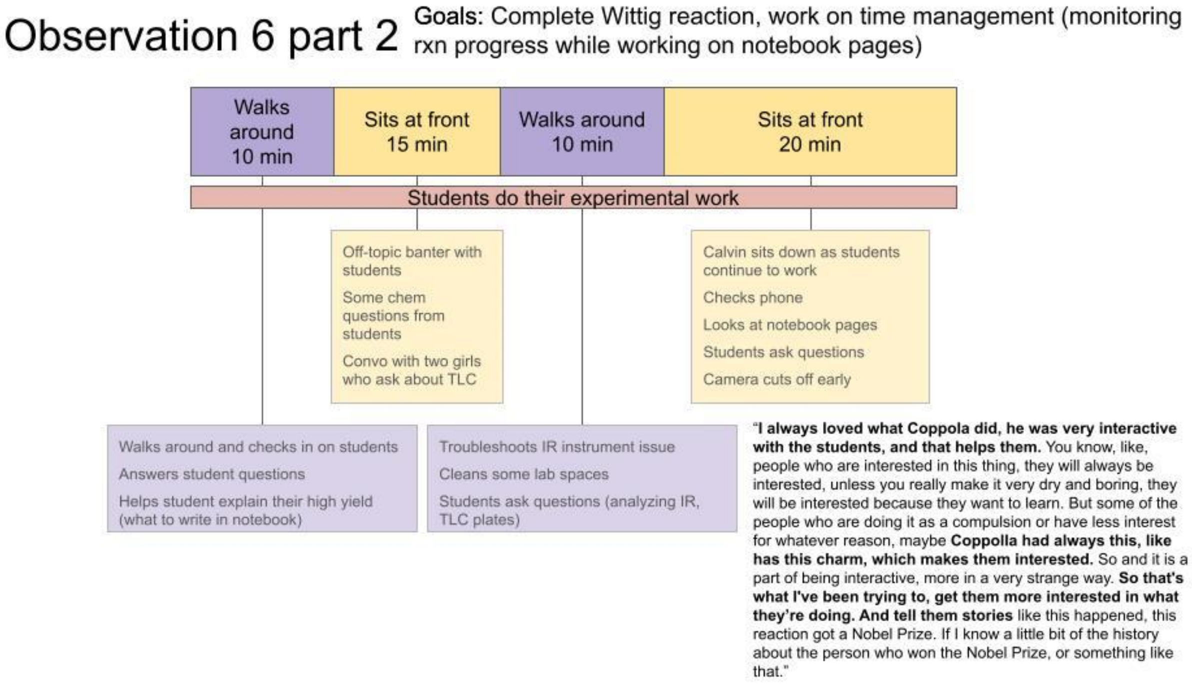
Walks around to check progress

Asks verbally if students completed the prelab

"I guess they're more efficient. So I do believe if you are more efficient, then you must be making less mistakes. And if you're making less mistakes, then you are learning I guess."

Video cuts off after 2 hours

**Figure 4.3h.** Calvin's observation summaries: observation 6 part 1.



Off-topic banter with students

Some chem questions from students

Convo with two girls who ask about TLC

Calvin sits down as students continue to work

Checks phone

Looks at notebook pages

Students ask questions

Camera cuts off early

Walks around and checks in on students

Answers student questions

Helps student explain their high yield (what to write in notebook)

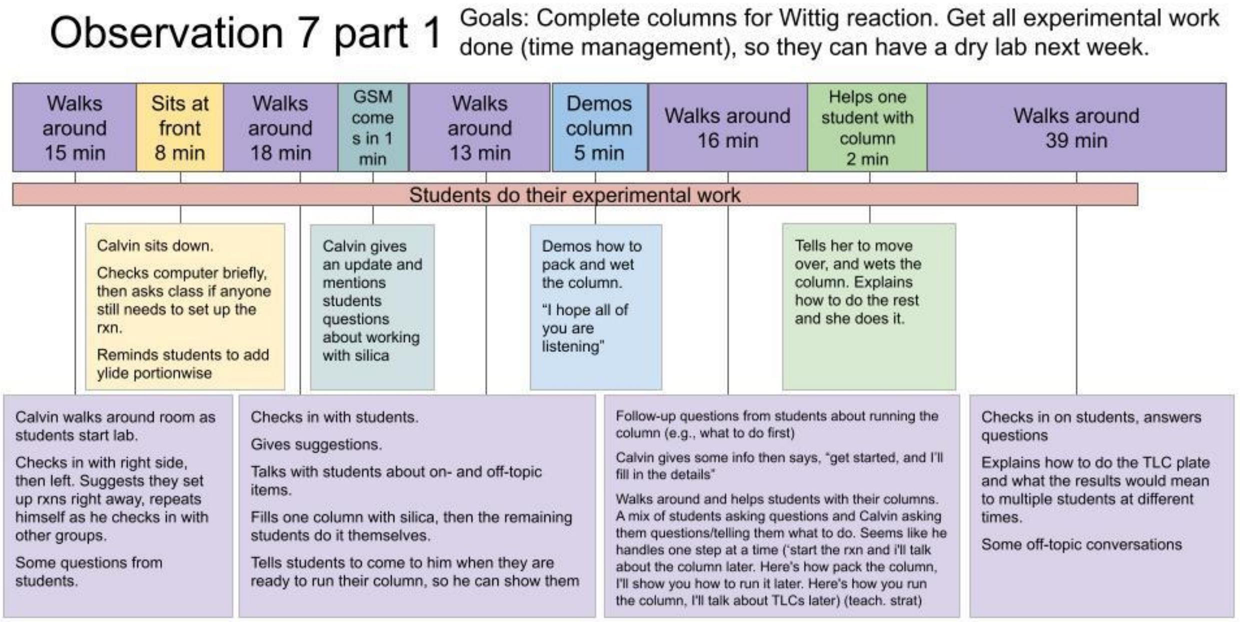
Troubleshoots IR instrument issue

Cleans some lab spaces

Students ask questions (analyzing IR, TLC plates)

"**I always loved what Coppola did, he was very interactive with the students, and that helps them.** You know, like, people who are interested in this thing, they will always be interested, unless you really make it very dry and boring, they will be interested because they want to learn. But some of the people who are doing it as a compulsion or have less interest for whatever reason, maybe **Coppolla had always this, like has this charm, which makes them interested.** So and it is a part of being interactive, more in a very strange way. **So that's what I've been trying to, get them more interested in what they're doing. And tell them stories** like this happened, this reaction got a Nobel Prize. If I know a little bit of the history about the person who won the Nobel Prize, or something like that."

**Figure 4.3i.** Calvin's observation summaries: observation 6 part 2.



Goals: Complete columns for Wittig reaction. Get all experimental work done (time management), so they can have a dry lab next week.

Calvin sits down.

Checks computer briefly, then asks class if anyone still needs to set up the rxn.

Reminds students to add ylide portionwise

Calvin gives an update and mentions students questions about working with silica

Demos how to pack and wet the column.

"I hope all of you are listening"

Tells her to move over, and wets the column. Explains how to do the rest and she does it.

Calvin walks around room as students start lab.

Checks in with right side, then left. Suggests they set up rxns right away, repeats himself as he checks in with other groups.

Some questions from students.

Checks in with students.

Gives suggestions.

Talks with students about on- and off-topic items.

Fills one column with silica, then the remaining students do it themselves.

Tells students to come to him when they are ready to run their column, so he can show them

Follow-up questions from students about running the column (e.g., what to do first)

Calvin gives some info then says, "get started, and I'll fill in the details"

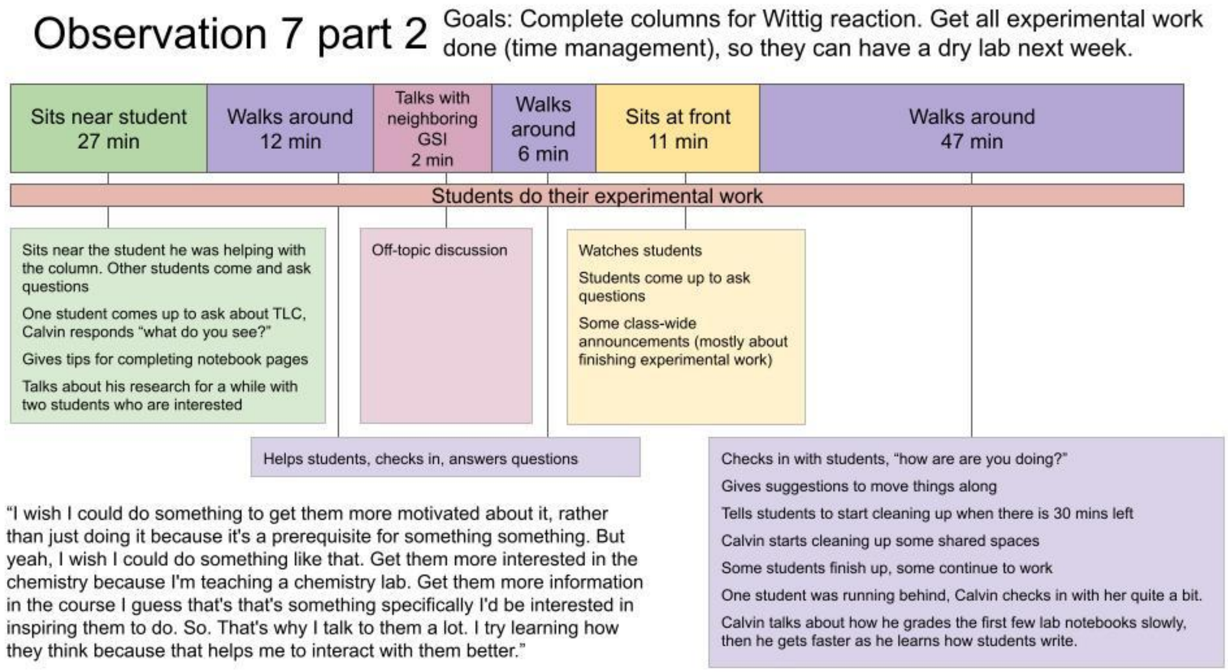
Walks around and helps students with their columns. A mix of students asking questions and Calvin asking them questions/telling them what to do. Seems like he handles one step at a time ('start the rxn and i'll talk about the column later. Here's how pack the column, I'll show you how to run it later. Here's how you run the column, I'll talk about TLCs later) (teach. strat)

Checks in on students, answers questions

Explains how to do the TLC plate and what the results would mean to multiple students at different times.

Some off-topic conversations

**Figure 4.3j.** Calvin's observation summaries: observation 7 part 1.



Goals: Complete columns for Wittig reaction. Get all experimental work done (time management), so they can have a dry lab next week.

Sits near the student he was helping with the column. Other students come and ask questions

One student comes up to ask about TLC, Calvin responds "what do you see?"

Gives tips for completing notebook pages

Talks about his research for a while with two students who are interested

Off-topic discussion

Watches students

Students come up to ask questions

Some class-wide announcements (mostly about finishing experimental work)

Helps students, checks in, answers questions

Checks in with students, "how are are you doing?"

Gives suggestions to move things along

Tells students to start cleaning up when there is 30 mins left

Calvin starts cleaning up some shared spaces

Some students finish up, some continue to work

One student was running behind, Calvin checks in with her quite a bit.

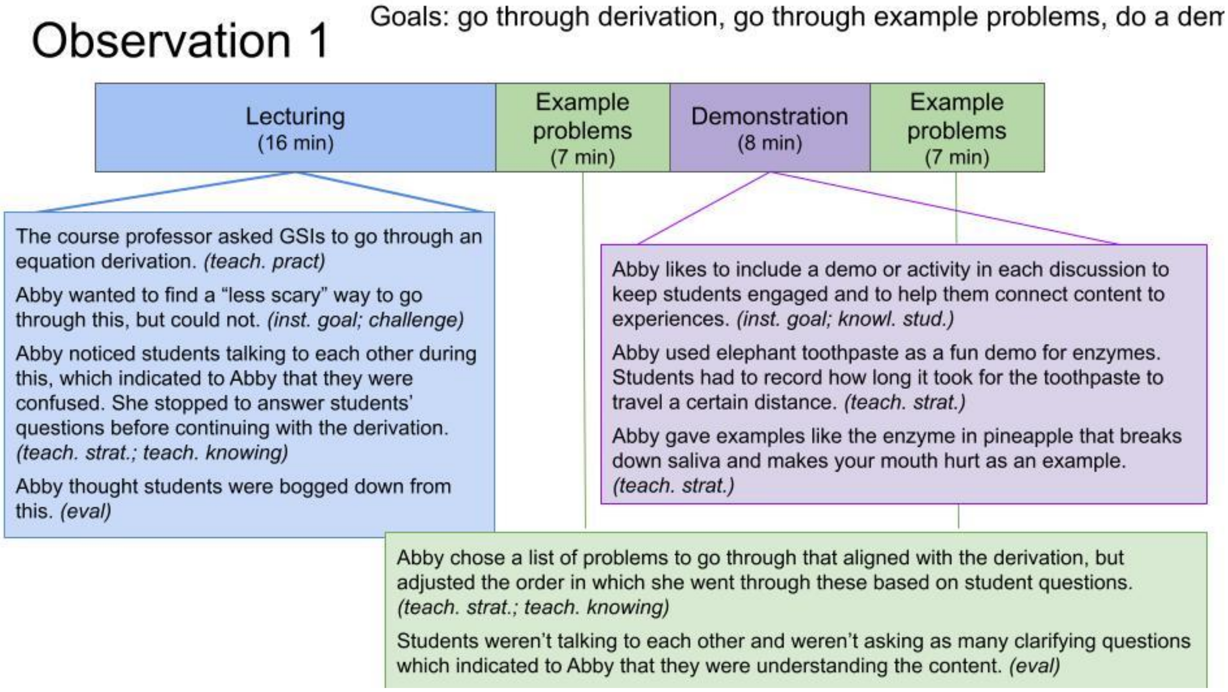
Calvin talks about how he grades the first few lab notebooks slowly, then he gets faster as he learns how students write.

"I wish I could do something to get them more motivated about it, rather than just doing it because it's a prerequisite for something something. But yeah, I wish I could do something like that. Get them more interested in the chemistry because I'm teaching a chemistry lab. Get them more information in the course I guess that's that's something specifically I'd be interested in inspiring them to do. So. That's why I talk to them a lot. I try learning how they think because that helps me to interact with them better."

**Figure 4.3k.** Calvin's observation summaries: observation 7 part 2.

### 4.9.4 Observation summaries: Abby

Semester 1: Biochemistry Discussion



Goals: go through derivation, go through example problems, do a de

The course professor asked GSIs to go through an equation derivation. *(teach. pract)*

Abby wanted to find a "less scary" way to go through this, but could not. *(inst. goal; challenge)*

Abby noticed students talking to each other during this, which indicated to Abby that they were confused. She stopped to answer students' questions before continuing with the derivation. *(teach. strat.; teach. knowing)*

Abby thought students were bogged down from this. *(eval)*

Abby likes to include a demo or activity in each discussion to keep students engaged and to help them connect content to experiences. *(inst. goal; knowl. stud.)*

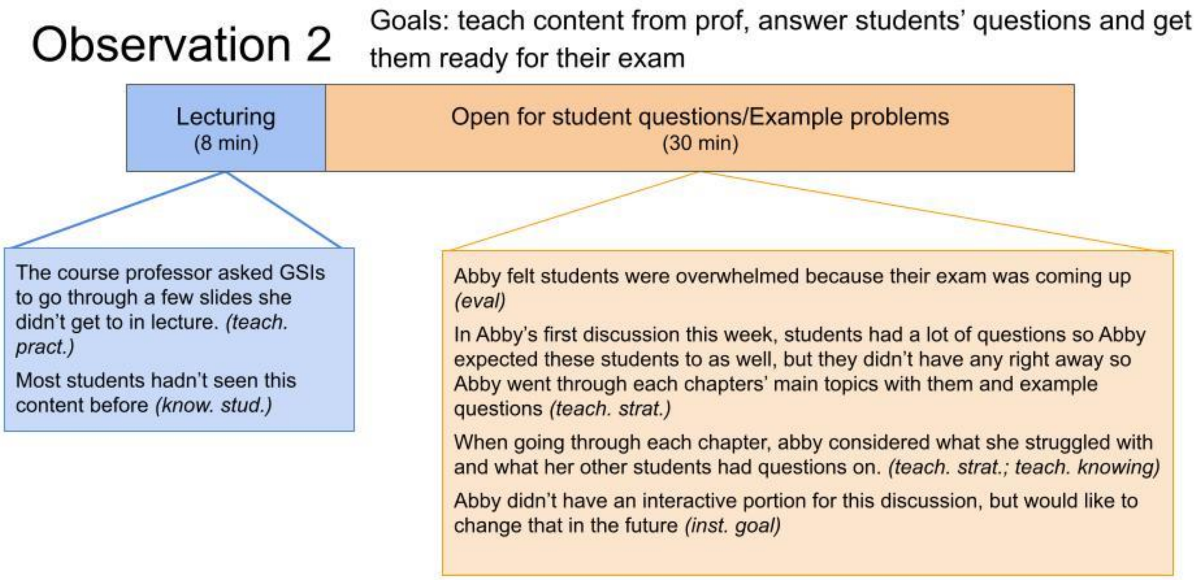
Abby used elephant toothpaste as a fun demo for enzymes. Students had to record how long it took for the toothpaste to travel a certain distance. *(teach. strat.)*

Abby gave examples like the enzyme in pineapple that breaks down saliva and makes your mouth hurt as an example. *(teach. strat.)*

Abby chose a list of problems to go through that aligned with the derivation, but adjusted the order in which she went through these based on student questions. *(teach. strat.; teach. knowing)*

Students weren't talking to each other and weren't asking as many clarifying questions which indicated to Abby that they were understanding the content. *(eval)*

**Figure 4.4a.** Abby's observation summaries: observation 1.



Goals: teach content from prof, answer students' questions and get them ready for their exam

The course professor asked GSIs to go through a few slides she didn't get to in lecture. *(teach. pract.)*

Most students hadn't seen this content before *(know. stud.)*

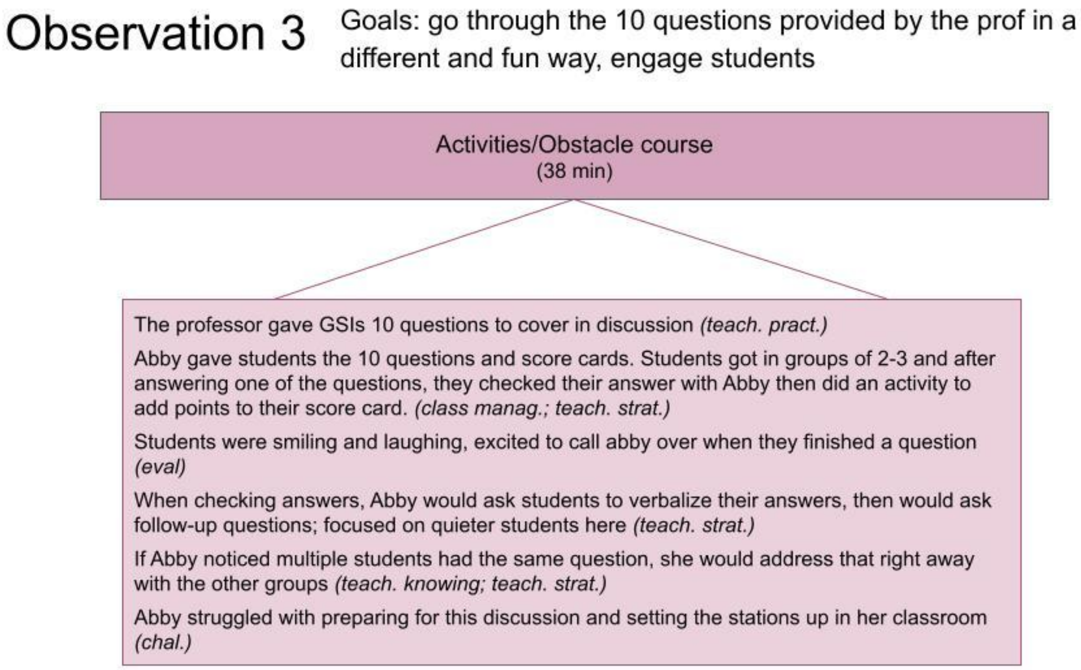
Abby felt students were overwhelmed because their exam was coming up *(eval)*

In Abby's first discussion this week, students had a lot of questions so Abby expected these students to as well, but they didn't have any right away so Abby went through each chapters' main topics with them and example questions *(teach. strat.)*

When going through each chapter, abby considered what she struggled with and what her other students had questions on. *(teach. strat.; teach. knowing)*

Abby didn't have an interactive portion for this discussion, but would like to change that in the future *(inst. goal)*

**Figure 4.4b.** Abby's observation summaries: observation 2.



Observation 3

Goals: go through the 10 questions provided by the prof in a different and fun way, engage students

Activities/Obstacle course
(38 min)

The professor gave GSIs 10 questions to cover in discussion *(teach. pract.)*

Abby gave students the 10 questions and score cards. Students got in groups of 2-3 and after answering one of the questions, they checked their answer with Abby then did an activity to add points to their score card. *(class manag.; teach. strat.)*

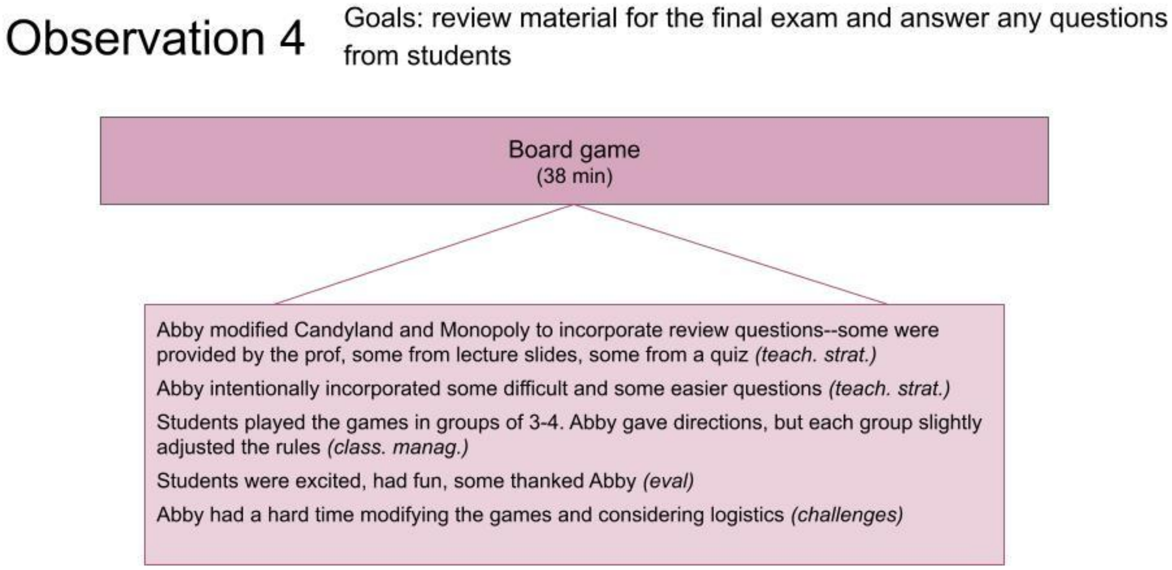
Students were smiling and laughing, excited to call abby over when they finished a question *(eval)*

When checking answers, Abby would ask students to verbalize their answers, then would ask follow-up questions; focused on quieter students here *(teach. strat.)*

If Abby noticed multiple students had the same question, she would address that right away with the other groups *(teach. knowing; teach. strat.)*

Abby struggled with preparing for this discussion and setting the stations up in her classroom *(chal.)*

**Figure 4.4c.** Abby's observation summaries: observation 3.



Observation 4

Goals: review material for the final exam and answer any questions from students

Board game
(38 min)

Abby modified Candyland and Monopoly to incorporate review questions--some were provided by the prof, some from lecture slides, some from a quiz *(teach. strat.)*

Abby intentionally incorporated some difficult and some easier questions *(teach. strat.)*

Students played the games in groups of 3-4. Abby gave directions, but each group slightly adjusted the rules *(class. manag.)*

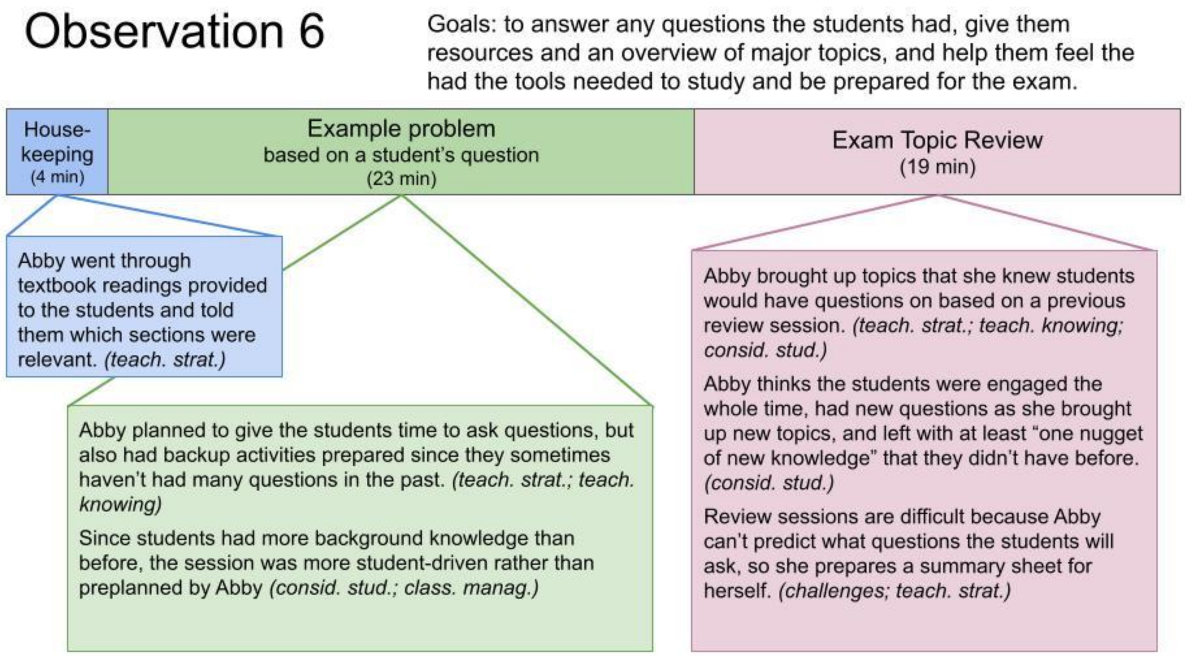
Students were excited, had fun, some thanked Abby *(eval)*

Abby had a hard time modifying the games and considering logistics *(challenges)*

**Figure 4.4d.** Abby's observation summaries: observation 4.

Semester 2: Bioinorganic chemistry discussion

Observation 5 was not analyzed due to technical complications.



Observation 6

Goals: to answer any questions the students had, give them resources and an overview of major topics, and help them feel the had the tools needed to study and be prepared for the exam.

House-keeping (4 min)

Example problem based on a student's question (23 min)

Exam Topic Review (19 min)

Abby went through textbook readings provided to the students and told them which sections were relevant. *(teach. strat.)*

Abby planned to give the students time to ask questions, but also had backup activities prepared since they sometimes haven't had many questions in the past. *(teach. strat.; teach. knowing)*

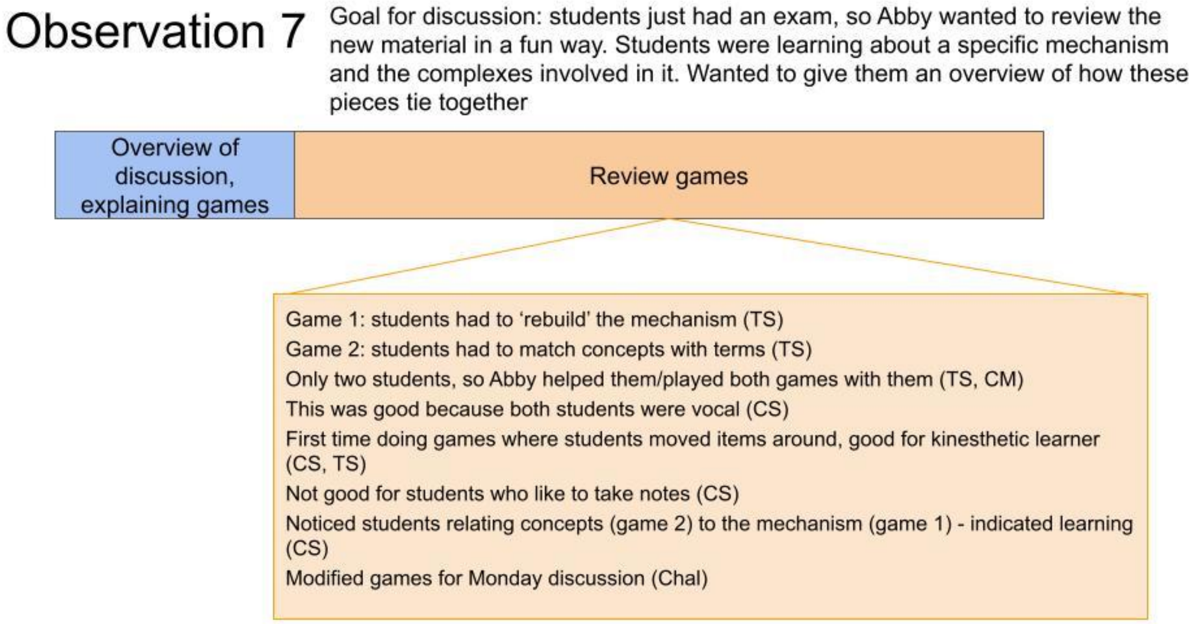
Since students had more background knowledge than before, the session was more student-driven rather than preplanned by Abby *(consid. stud.; class. manag.)*

Abby brought up topics that she knew students would have questions on based on a previous review session. *(teach. strat.; teach. knowing; consid. stud.)*

Abby thinks the students were engaged the whole time, had new questions as she brought up new topics, and left with at least "one nugget of new knowledge" that they didn't have before. *(consid. stud.)*

Review sessions are difficult because Abby can't predict what questions the students will ask, so she prepares a summary sheet for herself. *(challenges; teach. strat.)*

**Figure 4.4e.** Abby's observation summaries: observation 6.



Observation 7

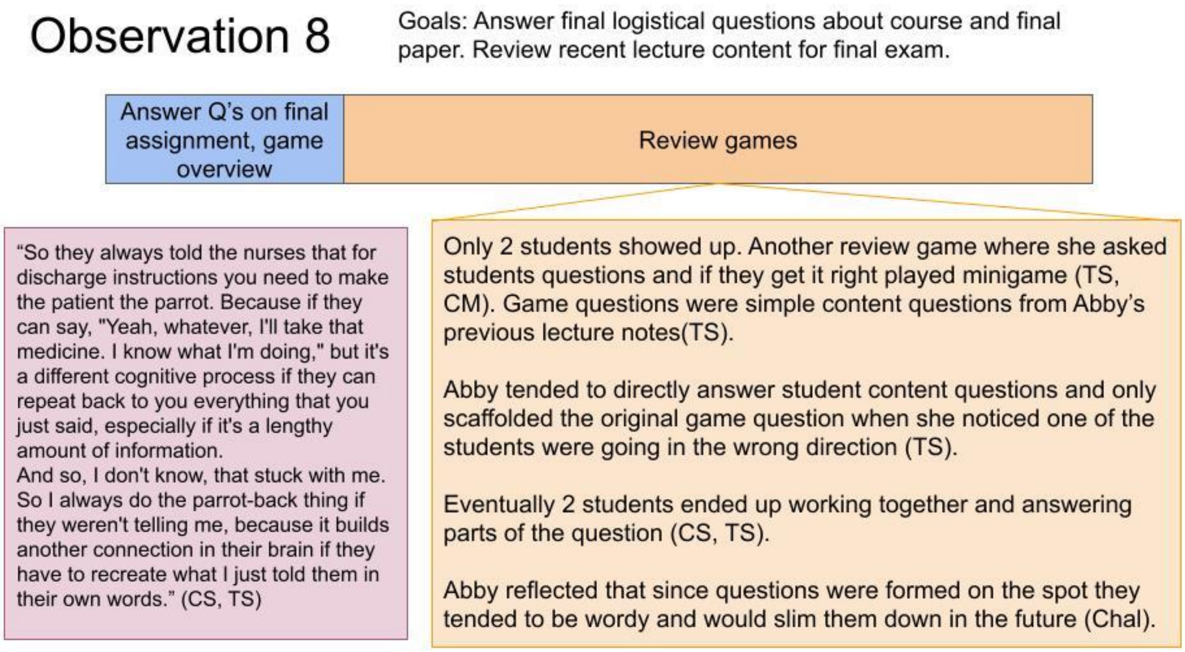
Goal for discussion: students just had an exam, so Abby wanted to review the new material in a fun way. Students were learning about a specific mechanism and the complexes involved in it. Wanted to give them an overview of how these pieces tie together

Overview of discussion, explaining games

Review games

Game 1: students had to 'rebuild' the mechanism (TS)
Game 2: students had to match concepts with terms (TS)
Only two students, so Abby helped them/played both games with them (TS, CM)
This was good because both students were vocal (CS)
First time doing games where students moved items around, good for kinesthetic learner (CS, TS)
Not good for students who like to take notes (CS)
Noticed students relating concepts (game 2) to the mechanism (game 1) - indicated learning (CS)
Modified games for Monday discussion (Chal)

**Figure 4.4f.** Abby's observation summaries: observation 7.



Observation 8

Goals: Answer final logistical questions about course and final paper. Review recent lecture content for final exam.

Answer Q's on final assignment, game overview

Review games

"So they always told the nurses that for discharge instructions you need to make the patient the parrot. Because if they can say, "Yeah, whatever, I'll take that medicine. I know what I'm doing," but it's a different cognitive process if they can repeat back to you everything that you just said, especially if it's a lengthy amount of information.
And so, I don't know, that stuck with me. So I always do the parrot-back thing if they weren't telling me, because it builds another connection in their brain if they have to recreate what I just told them in their own words." (CS, TS)

Only 2 students showed up. Another review game where she asked students questions and if they get it right played minigame (TS, CM). Game questions were simple content questions from Abby's previous lecture notes(TS).

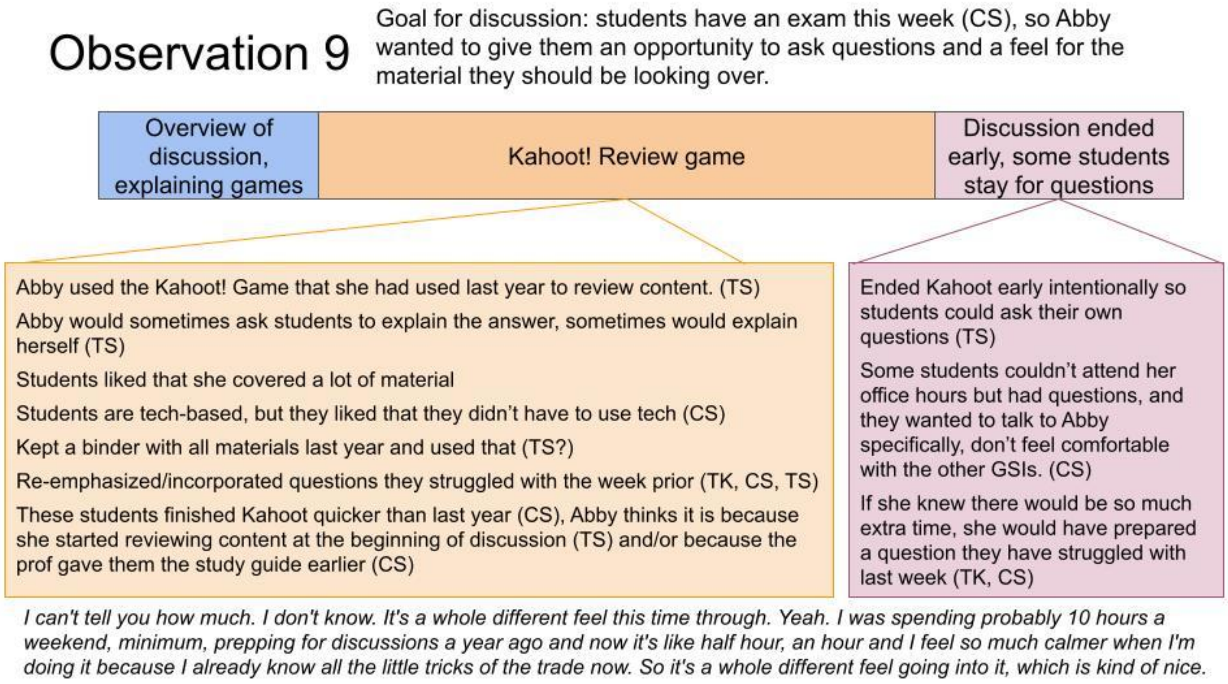
Abby tended to directly answer student content questions and only scaffolded the original game question when she noticed one of the students were going in the wrong direction (TS).

Eventually 2 students ended up working together and answering parts of the question (CS, TS).

Abby reflected that since questions were formed on the spot they tended to be wordy and would slim them down in the future (Chal).

**Figure 4.4g.** Abby's observation summaries: observation 8.

Semester 3: Biochemistry discussion



Observation 9

Goal for discussion: students have an exam this week (CS), so Abby wanted to give them an opportunity to ask questions and a feel for the material they should be looking over.

Overview of discussion, explaining games

Kahoot! Review game

Discussion ended early, some students stay for questions

Abby used the Kahoot! Game that she had used last year to review content. (TS)

Abby would sometimes ask students to explain the answer, sometimes would explain herself (TS)

Students liked that she covered a lot of material

Students are tech-based, but they liked that they didn't have to use tech (CS)

Kept a binder with all materials last year and used that (TS?)

Re-emphasized/incorporated questions they struggled with the week prior (TK, CS, TS)

These students finished Kahoot quicker than last year (CS), Abby thinks it is because she started reviewing content at the beginning of discussion (TS) and/or because the prof gave them the study guide earlier (CS)

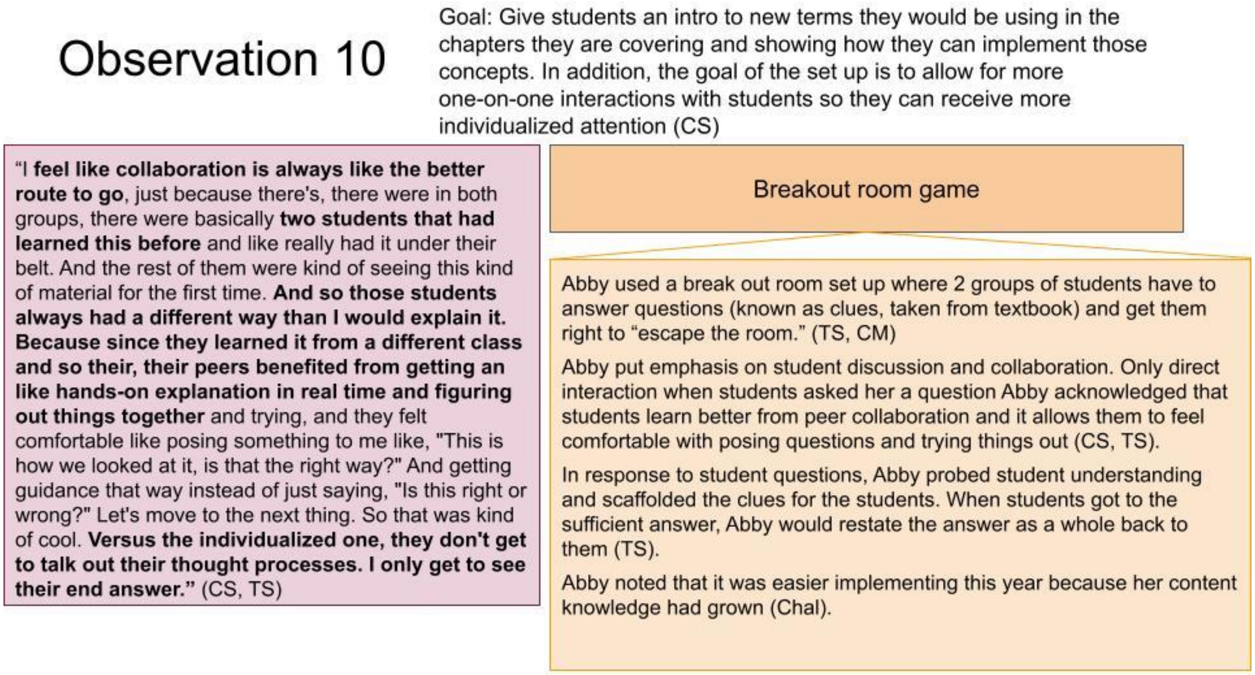
Ended Kahoot early intentionally so students could ask their own questions (TS)

Some students couldn't attend her office hours but had questions, and they wanted to talk to Abby specifically, don't feel comfortable with the other GSIs. (CS)

If she knew there would be so much extra time, she would have prepared a question they have struggled with last week (TK, CS)

*I can't tell you how much. I don't know. It's a whole different feel this time through. Yeah. I was spending probably 10 hours a weekend, minimum, prepping for discussions a year ago and now it's like half hour, an hour and I feel so much calmer when I'm doing it because I already know all the little tricks of the trade now. So it's a whole different feel going into it, which is kind of nice.*

**Figure 4.4h.** Abby's observation summaries: observation 9.



Observation 10

Goal: Give students an intro to new terms they would be using in the chapters they are covering and showing how they can implement those concepts. In addition, the goal of the set up is to allow for more one-on-one interactions with students so they can receive more individualized attention (CS)

"I **feel like collaboration is always like the better route to go**, just because there's, there were in both groups, there were basically **two students that had learned this before** and like really had it under their belt. And the rest of them were kind of seeing this kind of material for the first time. **And so those students always had a different way than I would explain it. Because since they learned it from a different class and so their, their peers benefited from getting an like hands-on explanation in real time and figuring out things together** and trying, and they felt comfortable like posing something to me like, "This is how we looked at it, is that the right way?" And getting guidance that way instead of just saying, "Is this right or wrong?" Let's move to the next thing. So that was kind of cool. **Versus the individualized one, they don't get to talk out their thought processes. I only get to see their end answer."** (CS, TS)

Breakout room game

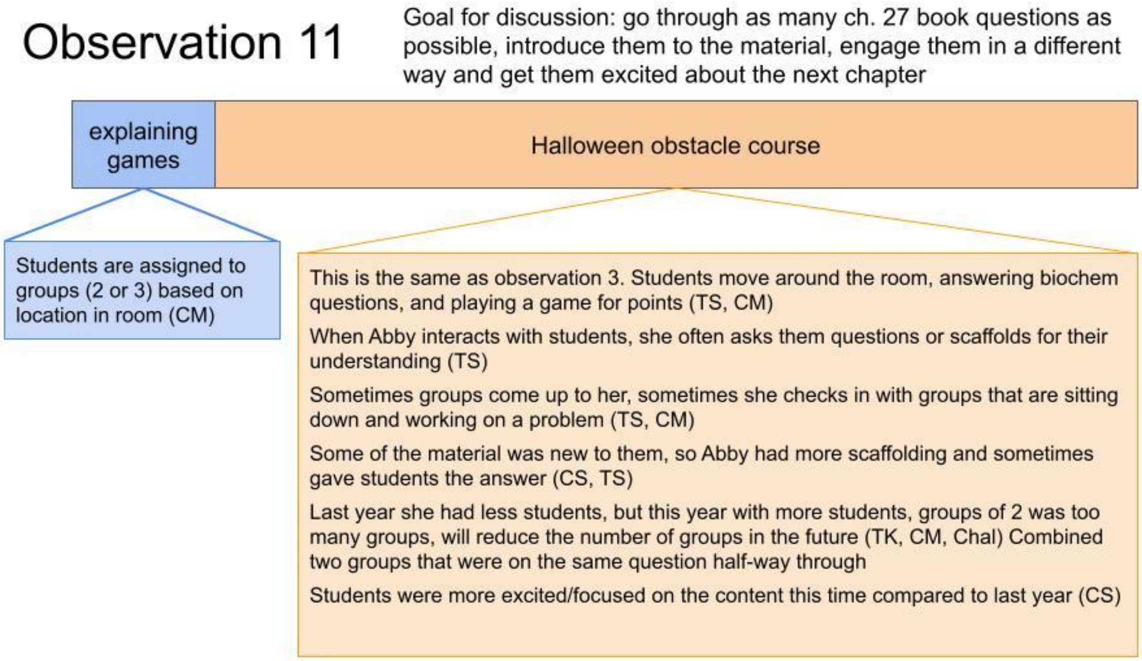
Abby used a break out room set up where 2 groups of students have to answer questions (known as clues, taken from textbook) and get them right to "escape the room." (TS, CM)

Abby put emphasis on student discussion and collaboration. Only direct interaction when students asked her a question Abby acknowledged that students learn better from peer collaboration and it allows them to feel comfortable with posing questions and trying things out (CS, TS).

In response to student questions, Abby probed student understanding and scaffolded the clues for the students. When students got to the sufficient answer, Abby would restate the answer as a whole back to them (TS).

Abby noted that it was easier implementing this year because her content knowledge had grown (Chal).

**Figure 4.4i.** Abby's observation summaries: observation 10.



Observation 11

Goal for discussion: go through as many ch. 27 book questions as possible, introduce them to the material, engage them in a different way and get them excited about the next chapter

explaining games

Halloween obstacle course

Students are assigned to groups (2 or 3) based on location in room (CM)

This is the same as observation 3. Students move around the room, answering biochem questions, and playing a game for points (TS, CM)

When Abby interacts with students, she often asks them questions or scaffolds for their understanding (TS)

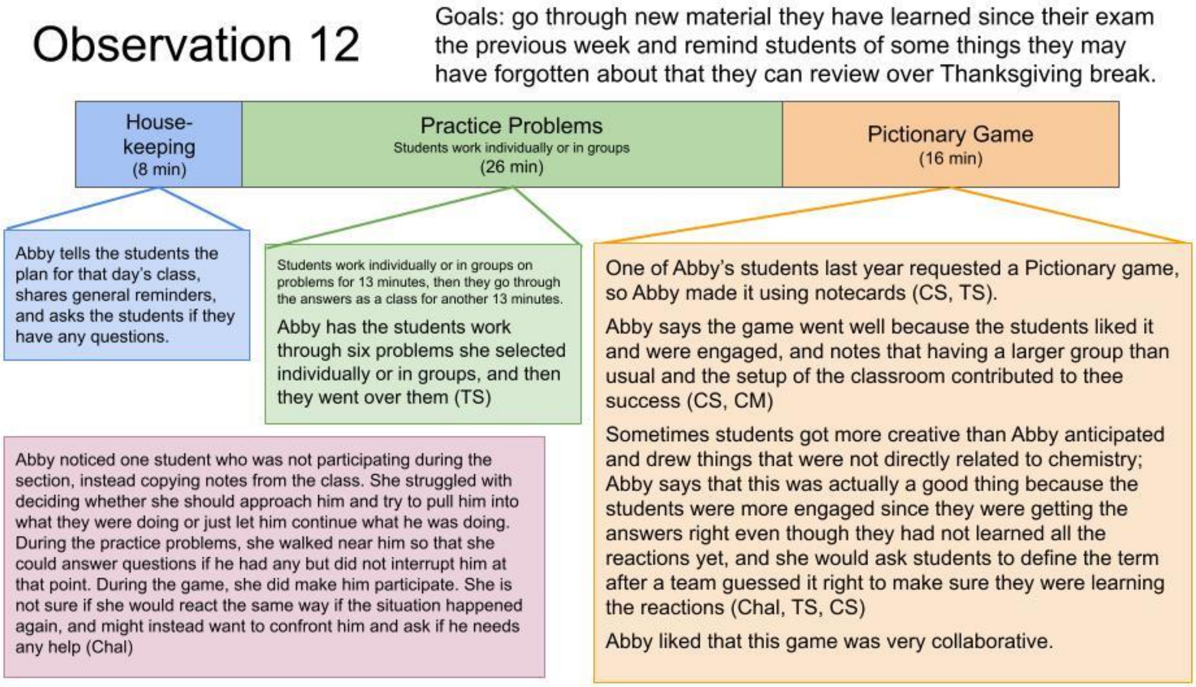
Sometimes groups come up to her, sometimes she checks in with groups that are sitting down and working on a problem (TS, CM)

Some of the material was new to them, so Abby had more scaffolding and sometimes gave students the answer (CS, TS)

Last year she had less students, but this year with more students, groups of 2 was too many groups, will reduce the number of groups in the future (TK, CM, Chal) Combined two groups that were on the same question half-way through

Students were more excited/focused on the content this time compared to last year (CS)

**Figure 4.4j.** Abby's observation summaries: observation 11.



Goals: go through new material they have learned since their exam the previous week and remind students of some things they may have forgotten about that they can review over Thanksgiving break.

Abby tells the students the plan for that day's class, shares general reminders, and asks the students if they have any questions.

Students work individually or in groups on problems for 13 minutes, then they go through the answers as a class for another 13 minutes.

Abby has the students work through six problems she selected individually or in groups, and then they went over them (TS)

One of Abby's students last year requested a Pictionary game, so Abby made it using notecards (CS, TS).

Abby says the game went well because the students liked it and were engaged, and notes that having a larger group than usual and the setup of the classroom contributed to thee success (CS, CM)

Sometimes students got more creative than Abby anticipated and drew things that were not directly related to chemistry; Abby says that this was actually a good thing because the students were more engaged since they were getting the answers right even though they had not learned all the reactions yet, and she would ask students to define the term after a team guessed it right to make sure they were learning the reactions (Chal, TS, CS)

Abby liked that this game was very collaborative.

Abby noticed one student who was not participating during the section, instead copying notes from the class. She struggled with deciding whether she should approach him and try to pull him into what they were doing or just let him continue what he was doing. During the practice problems, she walked near him so that she could answer questions if he had any but did not interrupt him at that point. During the game, she did make him participate. She is not sure if she would react the same way if the situation happened again, and might instead want to confront him and ask if he needs any help (Chal)

**Figure 4.4k.** Abby's observation summaries: observation 12.

## 4.10 Acknowledgements

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# Chapter 5

# Chemistry Graduate Teaching Assistants' Teacher Noticing

## 5.1 Initial Remarks

The work in this chapter investigates what chemistry GTAs notice in their classrooms and how they interpret what they notice. As described in Chapter 1, much of the research related to chemistry GTAs' teaching focuses on their teaching knowledge or content knowledge. Additional explorations of how GTAs manage their classrooms and assess student learning during class time are necessary to provide a more complete image of GTAs' teaching. Additionally, in Chapter 4, the author described how GTAs' reflections on their interactions with students during class promoted development of their teaching. Thus, the goal of this study was to describe what GTAs pay attention to during their teaching sessions and how they interpret student actions. The data set for this study included observations and interviews with six chemistry GTAs, each teaching different courses and with varying semesters of experiences as a GTA. Similar to the data collected for Chapter 4, each GTA was observed four times throughout one semester of teaching, and within 24 hours of each observation, a post-observation interview was conducted (the same post-observation interview protocol used for Chapter 4). Data analysis was guided by the theory of teacher noticing, which states that teachers necessarily choose to pay attention to certain aspects of their classroom as it is impossible to pay attention to everything at once. The teacher then interprets what they notice and chooses how to respond. Many factors influence what an individual teacher notices, how they interpret what they notice, and how they respond, such as their prior experiences and perceptions of their own duties as a teacher.

Through qualitative analysis, the author organized GTAs' teacher noticing into three categories: noticing evidence of student understanding, noticing student participation, and noticing the pacing of the teaching session. Findings suggest that the questions students asked GTAs served as GTAs' main indication of student learning and, in most cases, GTAs relied on the students to take initiative to ask questions. GTAs also often noticed when students were quiet, which was interpreted differently by different participants. Some GTAs interpreted this to mean that students were understanding the material, while others interpreted it to mean that students were not following along. Similarly, GTAs noticed whether students left their discussion or lab session on time or early, which indicated to lab GTAs that students understood and completed their tasks and indicated to discussion GTAs that students preferred to review content on their own.

Overall, GTA participants tended to rely on students to speak up and ask questions to assess their learning. Additionally, GTAs noticed relatively superficial actions (e.g., leaving class early) as signs of students' learning, and interpreted these in different ways. This work provides insight into what GTAs believe is important to pay attention to in their classrooms. Future research may specifically investigate chemistry GTAs' noticing of students' chemical thinking in discussion sessions or in an inquiry-based lab where students' observations ideally drive the session progression. Additionally, because our GTA participants relied on student initiative and other superficial observations, they may benefit from training that focuses on creating opportunities to elicit student thinking and implementing a variety of formative assessments. The author makes specific recommendations for both GTA training and further research on GTAs at the end of this chapter.

This chapter is being prepared as a publication to be submitted to a science education research journal. Dr. Nicholas Potter contributed to data collection. Diana Zhu and Marc Skriloff contributed to qualitative data analysis and writing portions of the manuscript. All remaining work, including data collection, data analysis, and manuscript writing were completed independently by the author.

## 5.2 Abstract

Chemistry GTAs have substantial facetime with undergraduate students at large research institutions where they lead discussion and lab sessions. Emerging research has demonstrated GTAs' content and teaching knowledge for introductory chemistry classes, but more is to be explored on how GTAs manage their classes in the moment and how they assess student learning during class time. We conducted classroom observations and post-observation interviews with six GTAs with various years of teaching experience and who were teaching a variety of classes (e.g., general chemistry discussion, biochemistry discussion, organic chemistry lab, computational chemistry lab, and more). Through qualitative analysis guided by the teacher noticing framework, we describe what chemistry GTAs notice, or pay attention to, in their teaching sessions and how

they interpret what they notice. We found that chemistry GTAs often paid attention to the types of questions that students asked but relied on their students to take initiative to ask questions in order to assess their learning. Also, GTAs often focused on superficial features of their sessions to assess learning, like whether students finished their tasks and left their session early. However, some GTAs noticed more sophisticated evidence of student understanding, such as when students connected content covered across multiple class sessions. The results from this study contribute to our understanding of how chemistry GTAs lead their sessions and evaluate student learning during their sessions. Results serve to inform potential training designs that can support chemistry GTAs' teacher learning through learning to notice—and to create opportunities to notice—significant features of their classrooms.

## 5.3 Background

### 5.3.1 Graduate teaching assistants

Graduate students routinely lead lab and discussion sessions in STEM departments at large research institutions. Often, this role starts during their first semester of graduate school, yet they receive little training to do so.[1,2] Research focused on understanding the experiences of GTAs within their respective teaching roles has identified that GTAs have ill-informed conceptions of how students learn; they believe students learn best when information is clearly presented to them.[3] As a result of this belief, GTAs are resistant to and struggle with implementing inquiry-based instruction.[4] This is often influenced by GTAs' prior experiences in their undergraduate education, which GTAs commonly draw on to inform their teaching.[5–7] This parallels research on instructors more generally, which shows that prior experiences influence instructors' beliefs about teaching and learning. Instructors' beliefs impact their instruction and development as instructors.[4,6,8–11] To evaluate student learning, research indicates that GTAs examine students' facial expressions, check students' grades, ask rhetorical questions like "do you understand?", and determine whether students could explain the concept themselves.[7] Other research indicates that GTAs use assessment strategies they feel are simple to use and require little added effort from the instructor and student, like asking students to write their "muddiest point" from the lesson.[4] Such methods may provide limited depictions of student learning; even so, many studies have recommended that GTA trainings increase their focus on formative and summative assessment strategies.[2]

Chemistry GTAs' instruction is also influenced by the context in which they teach. GTAs at research institutions have reported feeling that teaching is not valued in their departments, which inhibits their development as instructors.[2,7,12] GTAs consider their role as supplemental, viewing themselves as lab managers, tutors, someone to answer students' questions, and an approachable resource for students.[6,7] This perception of their role in their classrooms subsequently influences the actions they take to teach and assess their students (Chapter 4, this document).

Education researchers have recognized the challenges faced by GTAs and have implemented, evaluated, and published various training programs geared toward supporting GTAs in their respective roles. For example, Mutambuki and Schwartz[4] recently implemented a professional development program for chemistry GTAs and found that elements of the professional training were adopted by GTAs later in the semester. Prior to participating in the professional development, which focused in part on various formative assessments, GTAs relied on summative assessments like lab reports to assess student learning. The formative assessments discussed in this training included, for example, ungraded quizzes, asking students to identify their "muddiest point," and having students write for one minute in response to the question "what did you learn the most from the lesson?" After engaging in professional development, most GTAs reported using at least two types of formative assessments, which they described to be "vital in obtaining immediate feedback on students' areas of difficulties in learning, and for assessing conceptual understanding or knowledge transfer" (pg. 117).[4] However, researchers recognize that GTA challenges persist, and for training to be successful, the design must be contextualized to the university and department in which GTAs are situated.[4,7] In efforts to continue forward progress in understanding GTAs' experiences and conceptions of teaching, we used the teacher noticing framework to further describe GTAs' teaching.[13]

### 5.3.2 Teacher noticing

Teacher noticing is a useful framework for understanding how teachers manage their classrooms.[13] When instructors teach, they are presented with a "blooming buzzing confusion of sensory data" (pg. 5).[13] In other words, there are many different things happening simultaneously during a class session (e.g., students talking to each other, students recording notes, students asking questions, etc.). It is impossible for instructors to pay attention to every aspect of their classroom, so they choose to attend to (or notice) some specific element. Instructors then interpret what they notice and choose a response. This process represents a cycle, which includes the instructor noticing something in their classroom, interpreting what they notice, and responding—or not responding—based on their interpretation (see Figure 5.1). Once the instructor responds, they then choose to notice another aspect of their classroom, repeating the cycle. These parts of the teacher noticing cycle—notice, interpretation, and response—will be referred to as dimensions of teacher noticing.

The classroom elements that instructors notice provide insight into what instructors believe to be important to pay attention to and where they believe attention is not needed. To identify what instructors pay attention to, researchers have used a variety of methods including (a) having instructors record (write) elements of instruction that they notice as they watch video clips of instruction,[14–16] (b) having instructors reason out loud as they evaluate and grade student responses to exam questions,[17,18] and (c) having instructors record instances of student reasoning during their instruction, and reflect on those clips afterward.[19,20] Research in this area has demonstrated that novice teachers tend to focus on superficial features of classroom interactions, attend more so to teachers' actions than students', and view the lesson as a chronological but disconnected sequence of events. However, more experienced teachers tend to focus on students' actions, issues of content, and can more consistently identify students' thinking.[15,16,21–24] Additionally, Erickson[25] and Chan & Yau[24] found that novice teachers tend to focus on the learning of the whole class rather than individual students, which may incorrectly indicate lesson success to the instructor. The discrepancy between novice and experienced teachers may be because novice teachers do not know what to pay attention to and what to ignore.[26]

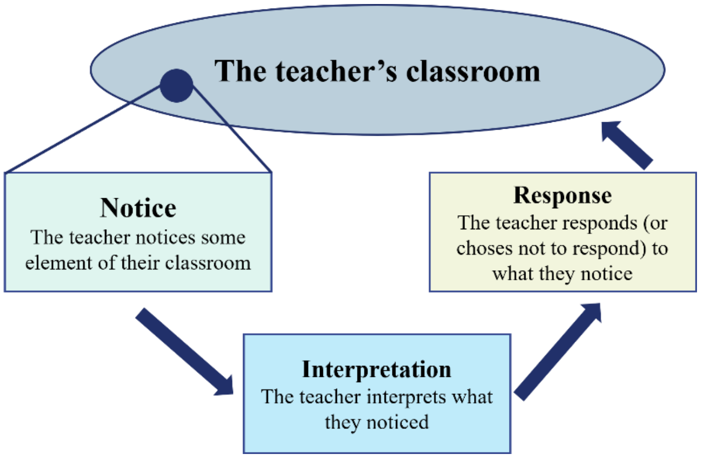

**Figure 5.1.** The teacher noticing cycle.

While noticing and interpreting have been conceptualized to occur simultaneously,[27–29] some researchers have isolated the dimension of interpretation.[30,31] Most of these studies are focused on how teachers make sense of students' understanding of content. For example, Sherin and van Es[30] characterized teachers' interpretations of students' mathematical thinking during videos of instruction as being descriptive (describing what they observed in the video), evaluative (evaluating the quality of interactions in the video), or interpretive (making inferences about what took place). They posit that the "interpretive" stance is the most sophisticated level of interpretation as it involves invoking substantive knowledge of content to examine classroom phenomena.[30] Understanding how teachers interpret what they notice provides insight into how teachers use their knowledge and experiences to make sense of what is observed.[32] Teachers' interpretations inform the actions they take or do not take in the classroom.[15,32]

Teachers' actions taken in response to interpreting what they notice may involve further questioning to draw out or guide students' understanding, explaining content in a different way, re-directing students' attention, referring students to other resources, and prompting discussion between students, among others.[27] Recently, van Es and Sherin[32] proposed an alternative third dimension of teacher noticing, which they refer to as shaping. This dimension is defined as "constructing interactions, in the midst of noticing, to gain access to additional information that further supports their noticing" (pg. 23)[32] and thus may involve asking questions to elicit students' understanding of content, which the teacher would then notice.

All dimensions of the teacher noticing cycle are profoundly influenced by teachers' prior experiences as instructors and learners, knowledge of teaching, cultural backgrounds, knowledge of content, and more.[14,25] Therefore, teacher noticing is highly contextual and can differ across teachers even within a single context. Additionally, highly sophisticated interpretation and response skills likely require sophisticated noticing skills.[24] Many efforts have been made to incorporate the development of pre-service teachers' noticing skills in training designs. For example, Sherin and van Es[30] designed a training in which preservice teachers were involved in video clubs. In club meetings, preservice teachers watched videos of instruction and then were provided prompting questions, such as "what stands out to you here?" to discuss with their peers. This design and other similar trainings focused on developing teacher noticing skills have proven to be successful in guiding teachers' attention to important aspects of student understanding and making more sophisticated interpretations of what they notice.[16,24,30,33] Teachers who can pay close attention to students' ideas and conceptions are better able to create opportunities for student learning.[34]

In accordance with the wider goal of better preparing GTAs for their teaching role, we aim to describe two dimensions of teacher noticing—notice and interpretation—for chemistry GTAs in this study. Chemistry GTAs reflect on their interactions with students in their classroom, and these reflections have prompted changes in their teaching (Chapter 4, this document). Understanding GTAs' teacher noticing may provide more detailed insight into GTAs' conceptions of teaching and learning as well as how training may support their development. Our work is guided by the research question: what do chemistry GTAs notice about their students during class sessions, and how do they interpret what they notice?

## 5.4 Methods

### 5.4.1 Context

This study was conducted at a large research institution in the Midwestern United States. Graduate students who hold GTA positions are expected to spend twenty hours per week completing research work and twenty hours on their teaching assistantship role, which includes preparing to teach, leading their sessions, holding office hours, grading, and more. GTAs' responsibilities are somewhat dependent on whether they are assigned to a lab or discussion. Lab GTAs are provided lab protocols by the course professor and are expected to lead their students through the protocol, explain relevant content, and guide students through data analysis. Discussion GTAs are generally expected to review the content taught in lecture and support students as they work through practice problems related to lecture content. Typically, GTAs are assigned to teach courses based on availability and if the GTAs' schedule aligns with course offerings. GTAs attend a two-day teacher training focused on departmental logistics, how to handle common situations with students, and expectations for their role before their first semester of graduate school. Throughout the semester, course professors hold weekly staff meetings to ensure all GTAs are informed of course logistics and are prepared for their sessions for the week.

### 5.4.2 Data collection

To investigate chemistry GTAs' teacher noticing in their lab and discussion sections, we conducted classroom observations and post-observation interviews with six GTAs. Our participants had a range of teaching experience and taught different courses: three participants were teaching lab sessions and three participants were teaching discussion sessions at the time of observation (see Table 5.1 for a summary of our participant population). All participants were given pseudonyms, informed consent was received by all participants and their students, and IRB approval was obtained for this study.

Data collection for this study was part of a larger study (Chapter 4, this document). Each participant was observed while they taught four times throughout one semester, except for Andrew who was observed three times. We conducted observations of discussion sessions using stationary cameras to capture the classroom (what students were doing, what the GTA was doing, and what was drawn on the board). Because stationary cameras were not able to capture the entirety of lab spaces and GTA-student interactions in labs, we collected observation data of lab sessions via a small wearable camera affixed to GTAs' lab glasses. This small recording device allowed us to view the session from the GTAs' perspective. For each observation, a researcher set up the equipment before the session started, left the room, and returned at the end of the session to collect the equipment. Discussion sessions are one-hour in length and lab sessions are 3-4 hours in length.

Within 24 hours after each observation, a researcher conducted a semi-structured interview with each participant during which the GTA reflected on their teaching session. The interview questions were geared toward capturing GTAs' goals for their session, indicators of success, and other perceptions of how their session went. The interviews typically lasted 20-30 minutes and served as our primary data source. The full post-observation interview protocol is included as supplemental information and is the same as was used for Chapter 4. The interviews were transcribed verbatim through an off-site service.

**Table 5.1**. Participant information.

| GTA | # Semesters as a GTA | Course | # Observations |
|---|---|---|---|
| Abby | 1 | Biochemistry discussion | 4 |
| Mallory | 1 | General chemistry discussion | 4 |
| Calvin | 2 | Organic chemistry II lab | 4 |
| Sol | 3 | Organic chemistry discussion | 4 |

| | | | |
|---|---|---|---|
| Grace | 4 | Computational chemistry lab | 4 |
| Andrew | 5 | General chemistry lab | 3[a] |

[a] Only three observations were conducted with Andrew due to technical complications.

### 5.4.3 Data analysis

Data analysis was guided by the theory of teacher noticing.[13] To conduct analysis, we analyzed one observation and post-observation interview at a time. We first watched the recorded teaching session and memoed times where teacher noticing may have occurred, based on our own perception. Our main goal of watching the observation first was to become familiar with the nature of the observed session and to gain context for what was mentioned in post-observation interviews. After watching an observation, we coded the associated post-observation interview.

Our codebook was created through conversations between the author and coauthors Diana Zhu and Marc Skriloff. We discussed the theory of teacher noticing and created our codebook to identify teacher noticing in interview transcripts. In this way, we used provisional coding methods,[35] where we identified predetermined codes based on our theoretical framework. Our codebook contained four codes: notice, interpretation, response-action, and response-no action. These codes are further described in Table 5.2.

**Table 5.2.** Our codebook, informed by the theory of teacher noticing.[13]

| Code | | Definition | Example |
|---|---|---|---|
| **Notice** | | **What the GSI explicitly notices/pays attention to/observes in their class during the observed session** | So usually in that section, if they're not understanding something, they'll turn to each other and start to talk. **And that's what they were doing during the derivation,** *so I stopped and tried to answer those questions.* **But with the problems, they weren't doing that. And if they did have a question, they were asking it to me and they were all very next-level questions. Like, they were following me along and asking follow-up questions, not clarifying questions.** Um, and they seemed, like when I would ask a follow-up question, like in the next problem related to the last problem, they would remember things. So I feel like they were following along with me. And that's how I gauged that it was going well.<br>(Abby post-observation interview 1) |
| Interpretation | | What the GSI interprets based on something they notice during the observed session/how they make sense of what they notice | |
| *Response* | *Action* | *How the GSI responds to what they notice* | |
| | *No action* | *Code when the GSI did not respond to something they notice, whether because they didn't know how to respond or chose not to respond* | |

The author and coauthors Diana Zhu and Marc Skriloff underwent this analysis process independently for one observation (Abby observation 1), then met to discuss coding of the post-observation interview. We discussed discrepancies and refined our codebook accordingly. For example, in Abby's first post-observation interview, she mentioned something she noticed in a previous session. Considering that we aim to describe teacher noticing within observed sessions, we decided to limit our teacher noticing to events that occurred within the observed session. We repeated this process with another observation and continued our conversations until we reached a consensus. With multiple researchers actively participating in data analysis, and allowing for negotiation and consensus building, we aimed to mitigate researcher bias.[36] Each researcher then independently coded a unique subset of interviews. Each week, all three researchers met to discuss independently-coded interviews until coding was complete.

After coding each interview for teacher noticing, interpretation, and response, we created spreadsheets to summarize noticing events for each participant, where each row contained a 'notice', the associated interpretation, and the associated response. This allowed us to view noticing events in a concise way. Through this process, we found that many GTAs' teacher noticing codes did not have an associated response-action or response-no action code with it. This is likely due to the nature of our interview as we asked GTAs to recall events but did not necessarily ask how they responded. Thus, we decided to focus on teacher noticing and interpretation during further analysis, aligning with other teacher noticing studies in mathematics education.[30,37,38] Once the spreadsheet was complete, we began identifying patterns in what GTAs notice. We listed these noticing patterns and continued to review themes as we looked for instances of teacher noticing that supported or conflicted with our initial identified patterns. Through this analysis, noticing patterns were grouped by similarities (i.e., noticings related to student understanding of content were grouped together, noticings related to students' participation in session activities were grouped together, and noticings related to the pacing of the teaching session were grouped together). These groupings became the three final categories of GTA teacher noticing, and each category is summarized in the results section below.

### 5.5 Limitations

Teacher noticing is a complex process that is difficult to capture in its entirety. In the study presented herein, we based our report of GTA teacher noticing on what GTAs mentioned in their post-observation interview. Asking teachers to recall events that occurred during a teaching session provides a window into what they pay attention to.[39] However, it is certainly possible that our participants noticed, interpreted, and responded to other events in their discussion or lab sessions that they did not recall in post-observation interviews. We aimed to avoid making assumptions about what was noticed or not noticed based solely on the observation recordings. A study that involves GTAs watching recordings of their teaching and reflecting on what they notice may provide more detailed insight into what GTAs notice during instruction and how they respond.[20,40,41] Additionally, our findings may not be generalizable to the general chemistry GTA population due to a relatively small participant population. However, our goal was not to provide generalizable cases but rather to deeply investigate a few cases that can provide a starting point for additional empirical studies focused on chemistry GTAs' teacher noticing.

## 5.6 Results

We sought to understand what chemistry GTAs notice and how they interpret what they notice during their lab and discussion sessions. Through qualitative analysis of interview and observational data with six chemistry GTAs, we have identified components of discussion and lab sessions that GTAs noticed during class. Chemistry GTAs' noticing events were inductively grouped into three categories: evidence of student understanding, student participation, and pacing of the teaching session. In the sections below, we describe these noticing events and GTAs' interpretations of such events to provide insight into what GTAs believe is important to pay attention to during class and how they interpret those events to inform their teaching.

### 5.6.1 Noticing evidence of student understanding

All GTA participants recalled events related to students' questions, which indicated student understanding, or lack thereof. GTAs noticed if students asked basic questions, more advanced questions, a lot of questions, or no questions (Figure 5.2). When students asked basic questions, GTAs interpreted that to indicate students were struggling with the content, which may be due to the way it is covered in lecture. For example, Sol (organic chemistry discussion GTA) said,

> *Generally, every discussion that I had yesterday a student asked, "What's a beta hydrogen and how do I determine it?" There's nothing special about a beta hydrogen and it's such an easy concept, but when it was covered in class, they didn't pick it up.*

Similarly, when GTAs noticed that students were asking a lot of questions, GTAs interpreted that to indicate students were confused or not prepared for an upcoming exam. In contrast, when students asked more advanced questions, that indicated to GTAs that students were learning. For example, Calvin (organic chemistry lab GTA) said, “They don't ask the same inexperienced questions anymore. The questions are much more fundamental. [...] Most of them, in most cases, know how to handle the reaction.”

The GTAs who noticed that students were not asking questions differed in their interpretations. This indicated to some GTAs that the session was going well, and students were understanding content. Grace (computational chemistry lab GTA) said, “there were long periods of time where there weren’t any questions because everyone was just working through the stuff.” Instances when students were not asking questions or when students were asking a lot of questions indicated to other GTAs that the students were not following along or understanding content. Mallory (general chemistry discussion GTA) said, “If there are no more questions, that'd imply that at least people either have said, “Okay, I think I understand this,” or have given up completely.”

GTAs also recalled when students made connections across sessions, which GTAs interpreted to indicate that students understand course content. For example, Andrew (general

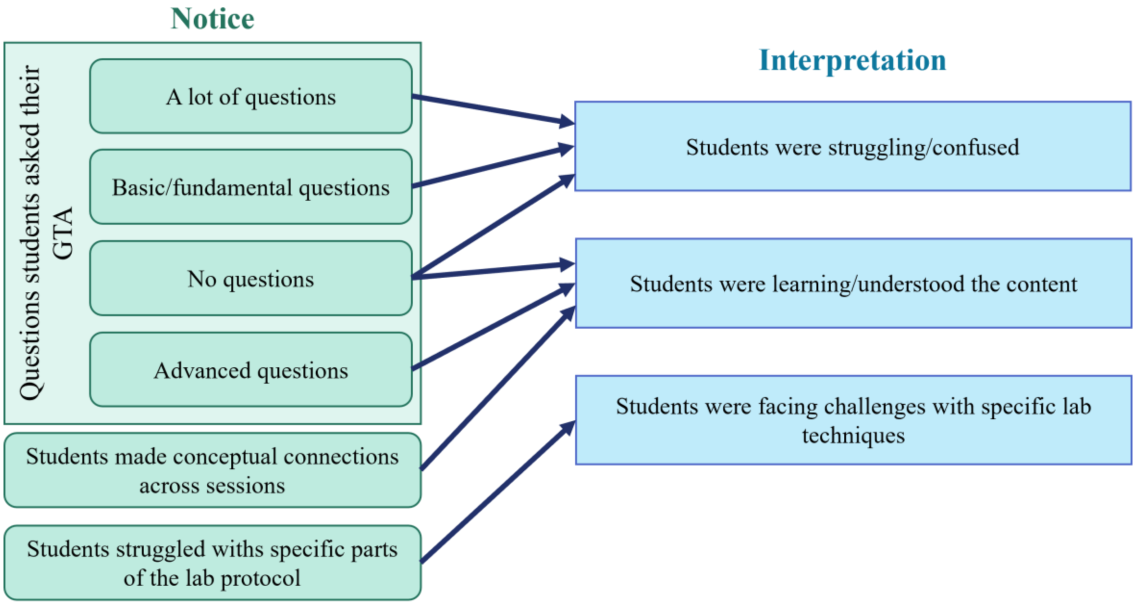

**Figure 5.2.** GTAs’ noticing events and interpretations related to student understanding of content.

chemistry lab GTA) discussed a worksheet question that students completed in class and said, “It was a fairly difficult question I was asking them about equilibrium, and I think they all got it because they were able to connect the dots between the two labs.”

Finally, lab GTAs noticed when students struggled with specific parts of the protocol, which indicated to them that certain lab techniques are challenging for students. Andrew (general chemistry lab GTA) said, “A lot of students had a long time trying to actually get the DCM to boiling, because they filled their beakers with huge amounts of water and took forever to heat up.”

### 5.6.2 Noticing student participation

GTAs also recalled the ways students participated in class (Figure 5.3). Some GTAs noticed when students worked together on tasks, which indicated to GTAs that students are trying to learn with each other and help each other with tasks. For example, Andrew (general chemistry lab GTA) said,

> *I started seeing groups, two or three teams, huddled together at the same table, working on answering questions together, trying to teach others how to use the equations to propagate uncertainty.*

Other GTAs noticed if students were not talking to each other and interpreted this in different ways. When this occurred during Abby’s lecture in her biochemistry discussion class, Abby interpreted it to mean that students were following along with her. When Mallory noticed students working independently during group work in her general chemistry discussion class, she interpreted it to mean that those students preferred to work independently. For example, Mallory said,

> *There are some kids who are better at group work than others. There’re some kids who learn better while working alone. There are some kids who will ask questions no matter whether they're in a group or they're in an individual setting. I think for some kids it is beneficial, but for other kids it's a neutral contribution.*

GTAs also noticed if students were quiet in general (not talking to each other or to their GTA), which indicated to GTAs that they did not know what was going on or were overwhelmed with course content. Andrew (general chemistry lab GTA) noted that he was unsure about how to interpret when students were quiet and said,

> *There were some people that are very quiet and [...] I think some of them... they might not have known what was going on, but I didn't know it because they weren't coming up to me. That's something I'm still trying to figure out.*

GTAs noticed if students were participating in class, which indicated to GTAs that students were learning and that the season went well. Sol (organic chemistry discussion GTA) said:

> *They actually really participated well. Sometimes I really have to drag them up to the board, especially when it's not just doing a problem, but everyone got up. Everyone participated, and they interacted well, so that went well.*

Finally, GTAs noticed if students were using external resources to complete tasks during class. For example, Andrew (general chemistry lab GTA) noticed students rewatching lecture videos during lab and interpreted this to mean that students were making connections between lecture and lab:

> *They were watching my video to make sure they knew how to do the calculations. And so that worked out really well. I'm really liking how students are able to use the prelab videos at the end and try to connect the dots and be able to do their experimental workup and try to connect that with what we taught in lecture.*

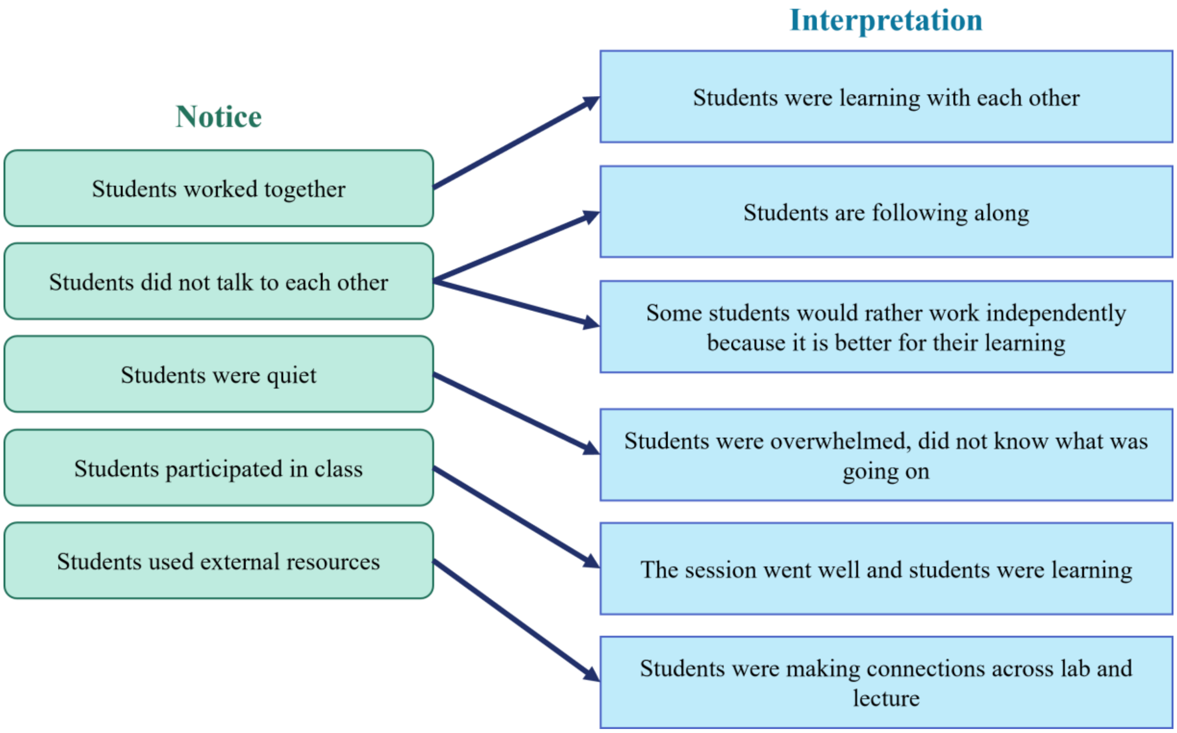

**Figure 5.3.** GTAs' noticing events and interpretations related to student participation.

### 5.6.3 Noticing the pace of the teaching session

All GTA participants reflected on the pace of the teaching session based directly on student actions or behaviors (Figure 5.4). GTAs anoticed that students worked at different paces, where some students were able to complete their tasks quicker than others. GTAs who noticed a student or group working slower than others interpreted it to mean that they were struggling with the material, especially if they were performing a technique for the first time. For example, Calvin (organic chemistry lab GTA) said, “Since they are doing it for the first time, they will be slow at it, and they need to be guided.” Grace (computational chemistry lab GTA) mentioned this is because students’ brains work differently:

> *The other thing that I noticed is that everybody works at different speeds, and there's not one specific way that you can do this. […] There's a way that everybody can do it differently based on how your brain works.*

GTAs also recalled when students completed their work by the end of class and left on time, which indicated to GTAs that students understood their tasks for the day and finished the required work or that the session went well. For example, Calvin (organic chemistry lab GTA) said, “It went totally fine. Got stuff done, we were supposed to do a certain experiment. Everyone did that. And yeah, it was alright.”

In some cases, GTAs reflected on times when students left the session early. Some GTAs interpreted this similarly to when they noticed that students left the session on time: students understood their assignment and finished their tasks. Other GTAs, however, interpreted this to mean that these students did not think staying in class for the entire duration was useful and wanted to study on their own. For example, Mallory (general chemistry discussion GTA) said, “A lot of students left because they wanted to study on their own and didn’t think it would be useful to stay in the session.”

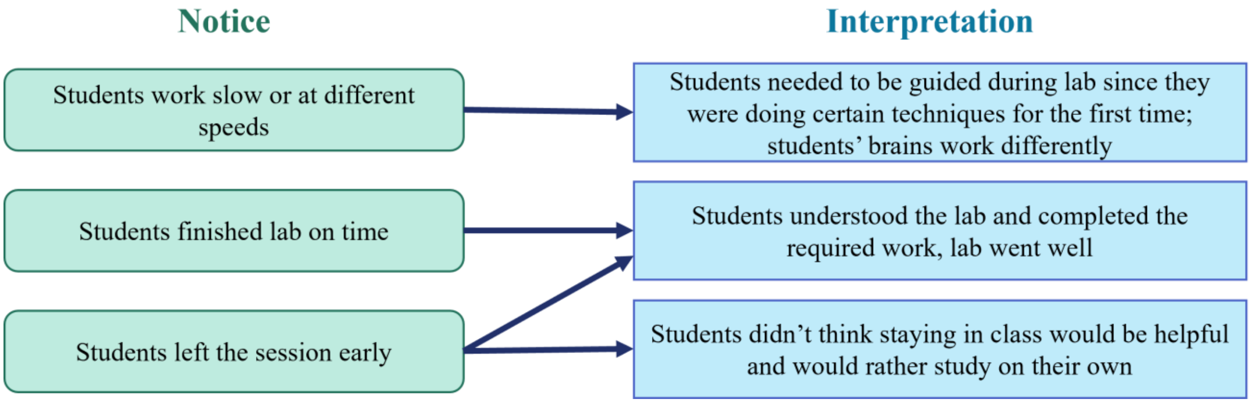

**Figure 5.4.** GTAs' noticing events and interpretations related to the pace of their teaching session.

## 5.7 Discussion

To identify what chemistry GTAs notice and interpret what they notice in their discussion and lab classrooms, we conducted observations and post-observation interviews with six chemistry GTAs teaching a variety of courses. In this study, we described two dimensions of the teacher noticing cycle: notice and interpretation.[13] GTAs' prior experiences as teachers and learners, knowledge of teaching, cultural backgrounds, knowledge of content, their own teaching context, and more likely influence what GTAs choose to pay attention to during their sessions,[14,25] and what GTAs pay attention to can influence their development as teachers (Chapter 4, this document). We presented three inductive categories of GTAs' teacher noticing: evidence of student understanding, student participation, and the pacing of the teaching session.

Our GTA participants' teacher noticing related to student understanding of content revealed that the questions students asked served as GTAs' main indication of student learning or lack thereof. In most cases, the GTAs relied on students taking initiative to speak up. Gauging student understanding solely by the questions asked by students does provide an indication of learning from the students willing to ask questions, but not all students. In a quote in section 5.5.2 above, Andrew mentioned that he noticed his students were quiet, and that may have indicated that they did not know what was going on, but he was not completely sure. He said he is still trying to figure out how to assess those students. A training focused on creating opportunities for students to share their thinking and leveraging their thoughts to move the class forward—an important teaching strategy to promote productive classroom discourse[42–45]—may support GTAs in further noticing students' understanding of course content. The types of questions teachers ask can also influence the ways students think about and learn course content.[46] van Es and Sherin[32] describe "shaping" as when teachers create opportunities to elicit student thinking, and our GTA participants rarely created these types of opportunities. Instead, GTAs relied on students to speak up and evaluated student learning based on other superficial factors, such as whether students were quiet and if students finished lab on time, which may be influenced by their limited teaching knowledge or conception of their role.

Our GTA participants placing focus on superficial factors is consistent with other studies that describe pre-service teacher noticing.[15,23,24] As described by Barnhart & van Es,[23] our GTA participants often demonstrated lower levels of sophistication of their noticing skills, as they attended to student behavior and classroom climate. When instructors exhibit limited skills in noticing, their potential to interpret and respond in more sophisticated ways is also limited.[23] In some cases, GTAs do demonstrate what Barnhart & van Es[23] describe as medium sophistication as they noticed individual students' thinking based on the questions asked by students. This skill can be leveraged in many ways, one of which is to improve GTAs' overall noticing skills, which can in turn support the development of their interpretation and response skills.

In some cases, multiple GTAs noticed similar events in their sessions but interpreted them differently. For example, when Abby and Grace noticed that students did not have questions, that indicated to them that students were following along and understanding material. In contrast, when Andrew noticed the same thing, he interpreted that to mean that students were not following along. Mallory was unsure if quiet students were understanding content or had given up learning. Additionally, the context in which GTAs teach may influence their noticing and interpretation. When GTAs noticed that students left the session early, Grace, Andrew, and Calvin, who taught lab sessions, interpreted that to mean the lab went well, students understood the lab, and completed their required work. When students left early from Mallory's discussion session, she interpreted that to mean that students felt it would be more helpful to study on their own.

Because GTAs interpret superficial actions as signs of students' learning, and because they interpret these differently, there is a need for GTAs to learn about formative assessments to more appropriately determine students' progress aligned with the learning goals for the course. In either case, GTAs may benefit from having a chance to implement and evaluate them in their own sessions, as in a GTA training program reported by Mutambuki and Schwartz.[4] This may help

GTAs obtain a clearer and more accurate account of student learning while also increasing student participation.

### 5.8 Implications

This study is the first to describe chemistry GTAs' teacher noticing in the classroom, which provides insight into what GTAs believe is important to pay attention to during instruction. This work can inform future studies that specifically investigate chemistry GTAs' teacher noticing of students' chemical thinking, as this framework has been used successfully in investigating pre-service and in-service teachers' noticing of students' mathematical and scientific thinking.[13,30,33] Similarly, identifying GTAs' teacher noticing in an inquiry lab, where GTAs need to lead students through their work, may provide interesting insights. Because our data involved GTAs' recall of events that happened in their session, a study in which GTAs watch their own recording during the post-observation interview may help GTAs recall key events during the class they may have otherwise forgotten.[40,41] Additionally, a study in which GTA participants watch a recording of a classroom session may be helpful in identifying similarities in teacher noticing across GTA participants.[16,37] Finally, a comparison of teacher noticing across a wider range of experience would be useful in further understanding the development of teacher noticing skills, such as novice GTA and a faculty member with experience teaching lab sessions. It would also provide insight into the potential influence of the impact of teaching roles, as GTAs are often given lab protocols and are asked to help students complete them, while faculty are the ones who develop the lab protocols.

While it may be instinctual for GTAs to focus on whether students finished the lab early or the specific questions individual students ask given GTAs' perceptions of their role, these types of indicators do not provide a complete picture of student learning.[21] We recommend that GTA training focus on developing GTAs' skills in creating opportunities for students to share their thinking and using this to guide students' learning, as leveraging students' thinking creates a more equitable and positive learning experience for students.[42–44] Simultaneously, instructors develop their own teaching knowledge as they learn more about how students think and grapple with content.[47,48] Methods such as approaching students as they work on tasks to ask open-ended questions are better indicators of student learning, as these types of questions usually require a student-generated explanation. Additionally, teaching strategies like "think-pair-share" help to develop peer relationships while also providing an opportunity for students to share their thinking.[49] Such methods do not rely on the content covered in class; they can be productive in both lab and discussion courses at any level.

As our GTA participants primarily relied on student actions to assess learning, GTA training programs could increase focus on both noticing student thinking and creating opportunities to elicit student thinking. One method to promote instructors' teacher noticing skills is to have instructors watch classroom recordings and reflect on what they observed. This can be done in pre-semester training, where GTAs watch recordings of other GTAs teaching and respond to prompts focused on specific aspects of the classroom.[15,30] If GTA training continues into the semester, training leaders may ask GTAs to record a 4–5-minute clip of their own teaching that demonstrates student thinking, and to share the recording with their peers. This process may encourage GTAs to elicit student thinking while they teach as their recordings will be shared with peers.[20] For such training programs to be most productive, GTAs must also reflect on their observations with peers. The observation and reflection should be guided by the dimensions of the teacher noticing framework and thus should focus on what the GTAs notice, how they interpret what they notice, and how they would respond. The teacher noticing framework can be a productive avenue to support GTA teacher learning in their own context as they engage in their teaching role.

## 5.9 Supporting information

### 5.9.1 Post-observation interview protocol

How did your section go?
What material are you covering right now?
What were the aims of your particular section?
What were the goals besides covering the content?
    Did you achieve your goals?
What parts of your section could have gone better?
What parts of your section went particularly well?
    How can you tell?
Have you taught this content before?
Did you use any teaching techniques that you haven't used before?
    Were there challenges with using these new techniques?
What went better than the previous week?
What do you feel like you could improve on for next week?

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# Chapter 6

# Closing remarks

This body of work constitutes a significant portion of chemistry education research on the teacher knowledge, identities, and development of chemistry GTAs. It provides insights into chemistry GTAs' experiences as instructors, including empirical evidence of GTAs' knowledge for teaching organic chemistry mechanisms, GTAs' general teaching knowledge and identities, how GTAs' knowledge and identities develop, and what GTAs pay attention to during their class sessions. Additional nuanced insights were provided by a case study in which the experiences of three chemistry GTAs were investigated over multiple semesters of teaching. By contextualizing GTA teacher learning in their unique teaching contexts, findings provide windows into the GTA experience through which additional research can further explore the unique experiences of these instructors. Findings also inform the design of targeted trainings to support GTAs in teaching lab and discussion sessions while also preparing them for potential futures in academia.