Perceptions of Undergraduate Physical Chemistry Instructors: Lessons from a Nationwide Survey, Assessment Analysis, and Reflections on Teaching and Learning

A DISSERTATION
SUBMITTED TO THE FACULTY OF THE
UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Gill H. Roehrig, Adviser

May 2016

In loving memory of my mom, Alice C. Fox (1955–2015).

Acknowledgements

I would like to express sincere gratitude to my adviser, Dr. Gill Roehrig. She has helped me grow as a chemist, educator and researcher, as well as advocate for communication and collaboration among chemists, educators and researchers, in order to achieve a united goal of outstanding undergraduate chemistry education.

I would like to acknowledge the members of my committee, Dr. Julie Brown, Dr. Lesa Clarkson and Dr. Frances Lawrenz, for their feedback and assistance throughout the research design, analysis, and writing process.

I am incredibly grateful to my students, the Department of Chemistry, and Dr. Amy Kampsen, Director of TRIO Student Support Services, for providing remarkable teaching opportunities that have been a genuine highlight of my graduate career.

This dissertation would not have been possible without the wonderful instructors who volunteered for my research. Thank you for your participation, enthusiasm and appreciation for chemical education research.

To my better half, John, thank you for standing by me, for helping me discover my inner strength, and for filling my life with love and happiness. I love you and I am excited to experience all of life’s adventures with you.

Finally, I would like to thank my parents, Joe and Alice, for their unwavering love and support. Dad, you always encouraged me to stand up for myself, my beliefs, and for those in need. Mom, you taught me kindness and patience, and you were always there for me when I needed a laugh, a cry, or a hug. Mom and Dad, I love you and I thank you, for I would not be where I am today without you.

Abstract

There are minimal policies in place that direct undergraduate education, and consequently there are scarce criteria that guide the pedagogical and curricular decisions of instructors. Thus, given their great degree of autonomy, instructors play a critical role in undergraduate education. In this dissertation, the perceptions of undergraduate physical chemistry instructors were investigated in three distinct, yet related studies, in order to understand how instructors' beliefs and attitudes impact their role as educators.

First, a nationwide survey of the undergraduate physical chemistry course was conducted to investigate the depth and breadth of course content, as well as how content is delivered and assessed. The results of the survey showed that a core group of thermodynamics and quantum mechanics topics were covered by almost all instructors, however there was a larger group of topics with a wide variability of coverage. Also, the majority of instructors created an instructor–centered environment, despite their degree of teacher preparation experience, and gave more mathematical assessment questions, which contradicted their conceptual leaning goals. Ultimately, the goal of the first study was to provide an awareness of the current state of physical chemistry education across the United States.

Second, an analysis of physical chemistry assessments was conducted to investigate characteristics of assessment questions including format, type of knowledge, and type of cognitive processes. The assessment analysis found that instructors used a subjective format more often than an objective format, there was an approximate equal distribution among questions that elicited factual, conceptual, and procedural knowledge, and the majority of questions utilized simple cognitive processes. Ultimately, the goal of the second study was to examine assessment practices of physical chemistry instructors across the United States.

Third, instructor reflections were utilized to investigate instructors' pedagogical content knowledge. Reflection questions were designed to elicit various components of pedagogical content knowledge, as well as how components of pedagogical content knowledge are associated with successful teaching moments, challenging teaching moments, and proposed changes. The analysis of reflections showed that instructors had a strong orientation towards teaching, a varied knowledge of curriculum, a weak knowledge of students' understanding, and a constantly evolving knowledge of instructional strategies. Ultimately, the goal of the third study was to use instructor reflections to provide a rich description of their pedagogical content knowledge.

Together, the three studies of this dissertation helped broaden the landscape of physical chemistry education research. The diverse levels of scale, ranging from nationwide perspectives to individual viewpoints, as well as varied methodologies, including both quantitative and qualitative approaches, helped expand and transform physical chemistry education research.

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List of Abbreviations

ACS	American Chemical Society
BBT	Blooming Biology Tool
PCK	Pedagogical Content Knowledge
PNOM	Particulate Nature of Matter
U.S.	United States

1. Introduction

1.1. Organization of Dissertation

This dissertation is organized into six chapters. Chapter 1 provides an overall organization and rationale for the research. Chapter 2 contains a literature review that serves to ground the dissertation in the context of prior work. Chapters 3–5 each contain a single study, where each chapter includes a rationale, literature review, methodology, results, and discussion specific to that study. Chapter 6 serves as a concluding chapter that discusses overarching findings from all three studies, implications for teaching, and future research.

The first study, found in Chapter 3, is a nationwide survey that investigated the current state of physical chemistry education across the United States (U.S.) (Fox & Roehrig, 2015). A survey was developed to measure the depth and breadth of course content, how content is delivered and assessed, and the beliefs and experiences of instructors. The goal of the first study was to identify trends among physical chemistry courses across the U.S., and to use the implications of these trends to inform the two subsequent studies.

The second study, found in Chapter 4, is an investigation of physical chemistry assessments. The nationwide survey found a discrepant relationship between instructor reported learning goals and assessment questions (Fox & Roehrig, 2015). The goal of the second study was to further explore this relationship through an investigation of the current state of physical chemistry assessments. Specifically, the second study examined the format, type of knowledge, and type of cognitive processes of assessments questions.

The assessment analysis also incorporated data collected via the nationwide survey so that assessment practices among different instructors and institutions could be explored.

The third study, found in Chapter 5, examined what instructor reflections reveal about their pedagogical content knowledge (PCK). The nationwide survey reported the need for further research regarding the PCK of instructors due to pedagogical trends including minimal teacher preparation experience and instructor dominated discourse (Fox & Roehrig, 2015). The goal of the third study was to use instructor reflections to provide a rich description of the PCK of physical chemistry instructors. The reflection questions asked instructors to describe successful and challenging teaching moments, as well as what they strived to change about their teaching, all while eliciting instructors' orientation towards teaching, knowledge of curriculum, knowledge of students' understanding, and knowledge of instructional strategies.

Together, the three studies of this dissertation serve to broaden the landscape of physical chemistry education research. The nationwide survey painted a picture of physical chemistry education at a relatively large scale, which then directed the smaller scale focus of the assessment analysis and reflections on teaching and learning. In addition to the spectrum of scale, the three studies also represent a spectrum of methodologies. While the nationwide survey used primarily quantitative methodologies, the assessment analysis used both quantitative and qualitative methodologies and the reflections on teaching and learning used primarily qualitative methodologies. The range of both scale and methodologies evident in this dissertation serve to expand and transform physical chemistry education research.

1.2. Rationale

There are minimal policies in place that direct undergraduate education, and consequently there are scarce criteria that guide the pedagogical and curricular decisions of instructors. Thus, given their great degree of power and autonomy, instructors play a critical role in undergraduate education. An investigation of the perceptions of undergraduate instructors is a key component for the continued advancement of undergraduate education. The purpose of this dissertation is to investigate the perceptions of physical chemistry instructors, and how those perceptions impact their role as educators.

In undergraduate chemistry education, there are minimal standards in place that direct the decisions of chemistry departments. Such decisions range from the design of the chemistry degree program to daily classroom events, including what to teach, how to teach, and how to assess. While the American Chemical Society (ACS) has guidelines and evaluation procedures in place that chemistry departments must follow in order to achieve ACS certification, such policy provides broad recommendations rather than specific standards (American Chemical Society Committee on Professional Training, 2015).

One example of the broad ACS guidelines is course content. The certification requirements state that students must take a year of general chemistry as introductory coursework. Next, students take foundational coursework which consists of one semester of analytical chemistry, biochemistry, inorganic chemistry, organic chemistry, and physical chemistry. Finally, students take in–depth course work which consists of four additional advanced courses in any area of chemistry (American Chemical Society

Committee on Professional Training, 2015). Beyond identifying the traditional areas of chemistry, the certification requirements do not provide specific concepts or skills that students should master in each course. Instructors, then, have the responsibility and influence to make decisions regarding the details of course content. Such decisions include which topics to cover or omit, as well as the depth versus breadth of various topics. Given this instructor freedom, what a student is exposed to in a chemistry course at one institution can vary considerably from what a student is exposed to at a different institution.

Another example of the broad ACS guidelines includes teaching strategies. The certification requirements state that “faculty should incorporate pedagogies that have been shown to be effective in undergraduate chemistry education” (American Chemical Society Committee on Professional Training, 2015, p. 8). Examples of effective pedagogies are provided, such as problem–based learning, inquiry–based learning, peer–led instruction, learning communities, and technology–aided instruction, however there is no explanation for how to successfully implement these strategies. Thus, instructors have the freedom to utilize any teaching approach of their choosing, provided it can be described as an effective pedagogy. Given the diversity in instructor teaching philosophies, varying pedagogies are evident in undergraduate chemistry education. Not only are students at different institutions exposed to different concepts, they also learn about those concepts in different ways based on the strategies implemented by their instructor.

A final example of the broad ACS guidelines involves assessment. The certification requirements do not provide any mandate for how to assess student understanding (American Chemical Society Committee on Professional Training, 2015). The ACS Division of Chemical Education Examinations Institute has developed final, cumulative exams for each area of chemistry, however instructors are not required to use these exams (American Chemical Society Division of Chemical Education Examinations Institute, 2015). ACS exams are comprised completely of multiple–choice questions which assess students' conceptual and procedural understanding. While instructors are not required to administer ACS exams, instructors may elect to give ACS exams as a means to make internal institutional comparisons between current and past students, or between students enrolled in the same course but with different instructors. The ACS also publishes national exam statistics which allows instructors to make external comparisons and examine how their students perform against the national norm. Such internal and external comparisons are benefits of the ACS exams, however the benefits are constrained to a multiple–choice testing format and are limited to the instructors who elect to use the exams.

In summary, the ACS guidelines contain broad standards regarding course content, pedagogy, and assessment, and these broad standards can be perceived and implemented in various ways by different instructors. Consequently, detailed benchmarks regarding what to teach, how to teach, and how to assess are lacking for undergraduate chemistry education.

Due to the minimal policies present in undergraduate chemistry education, instructors have considerable independence in their pedagogical and curricular decisions. Given this independence, understanding instructor perceptions, and how those perceptions translate into action, is crucial for the advancement of undergraduate chemistry education. Prior and ongoing research has investigated the role of the instructor in undergraduate chemistry education. Such research is prevalent for general chemistry, but is quite minimal for advanced chemistry courses, such as physical chemistry. While the development of general chemistry education is important, all areas of chemistry should be the focus of education research in order to establish effective teaching and learning experiences that span the undergraduate chemistry curriculum.

Physical chemistry education is the focus of this dissertation. By definition, “physical chemistry is the study of how matter behaves on a molecular and atomic level and how chemical reactions occur” (American Chemical Society, 2015, para. 1). In physical chemistry, students learn about the physical properties of atoms and molecules and how those properties impact chemical reactions. To develop their chemical understanding, students use theories of physics and mathematical computations. Physical chemistry predominantly serves upper–level undergraduate students in their pursuit of a bachelor’s degree in chemistry.

This dissertation strives to explore instructor perceptions of the teaching and learning of physical chemistry. This will be accomplished through a nationwide survey, an analysis of assessments, and instructor reflections. The implications of this research will play a role in the advancement physical chemistry education.

2. Literature Review

Every semester, thousands of undergraduate students across the United States (U.S.) take a course in general chemistry. Aspiring chemistry majors are not the only students who take general chemistry; students pursuing a degree in the physical sciences, life sciences, engineering, and professional health fields are frequently required to take general chemistry. Additionally, general chemistry is often a choice for non–science majors to fulfill the physical science requirement of a liberal arts education. Thus, general chemistry serves to educate a broad spectrum of students. Given the vast student body that enrolls in general chemistry, general chemistry education research is an expansive field that has investigated numerous aspects of teaching and learning general chemistry. In contrast to general chemistry education, there is a much narrower research focus on upper–level undergraduate chemistry courses, in particular physical chemistry. The goal of this dissertation is to extend physical chemistry education research by using instructor perceptions to investigate best practices for the teaching and learning of physical chemistry.

2.1. Physical Chemistry Education Research

Physical chemistry education research is a much newer and emerging field of chemical education research. One explanation for the slower development of physical chemistry education research is that while general chemistry serves a broad spectrum of students, chemistry majors tend to be the predominant audience for physical chemistry. Thus, far fewer students take physical chemistry compared to general chemistry, and the future academic and career goals of students in physical chemistry tend to be less heterogeneous than that for general chemistry. Despite the differences in quantity and diversity of students enrolled in general and physical chemistry, there is room for growth in physical chemistry education.

Early physical chemistry education research focused more on what to teach, rather than how to teach (Combs, 1976), but over time the field of physical chemistry education research has slowly transformed. Prior research has attempted to identify what the challenges of teaching and learning physical chemistry are, as well as investigate strategies to overcome these challenges (Bain, Moon, Mack & Towns, 2014). Three prominent challenges regarding the teaching and learning of physical chemistry have been identified: the role of mathematics, student and instructor perceptions, and the pedagogical content knowledge (PCK) of instructors. Details of these challenges, as well as ongoing strategies to improve the teaching and learning of physical chemistry are discussed in the following subsections.

2.1.1. The Role of Mathematics in Physical Chemistry

One of the biggest challenges of physical chemistry education is the role of mathematics, yet there is an unclear relationship between student mathematical ability and success in physical chemistry. Prior research has investigated the role of mathematics but has produced conflicting results.

One study showed that there is a positive relationship between student mathematical ability and success in physical chemistry (Hahn & Polik, 2004). This positive relationship was evident given the significant, positive correlation between students' average mathematics grade with students' final grades in physical chemistry. There was also a positive, albeit smaller correlation, between the number of prior mathematics courses with students' final grades in physical chemistry. Thus, Hahn and Polik (2004) found that students' mathematical skills are an important factor in predicting their success in physical chemistry.

A second study agreed with the positive relationship between mathematical ability and success in physical chemistry, but only for certain mathematical skills (Nicoll & Francisco, 2001). A significant, positive correlation was found between strong word problem skills and students' final grades in physical chemistry. When investigating calculus and algebraic skills, a significant, but much smaller, positive correlation was found between strong calculus skills and students' final grades in physical chemistry, and no correlation was found between strong algebraic skills and students' final grades in physical chemistry. Additionally, the study investigated the relationship between student perspectives and success in physical chemistry, and found a significant, positive correlation between students who reported positive perceptions of physical chemistry, including confidence and an interest in the course, with higher final course grades. Thus, while there is a positive relationship between mathematical ability and success in physical chemistry, Nicoll and Francisco (2001) found that not all mathematical skills equally impact success in physical chemistry, and factors beyond mathematical ability also play a significant role in students' performance in physical chemistry.

A third study investigated the relationship between success in prior mathematics and science courses with success in physical chemistry and concluded that there is no relationship between success in algebra and physical chemistry, but that there is a significant, positive relationship between success in calculus and physical chemistry (Derrick & Derrick, 2002). In addition to mathematics courses, this study also found a significant, positive relationship between students' final grades in organic chemistry, analytical chemistry, and physics, with students' final grades in physical chemistry. Thus, Derrick and Derrick (2002) found that while mathematical ability impacts student performance in physical chemistry, not all areas of mathematics play a significant role, and prior science knowledge can be more important than certain prior mathematical knowledge.

Given the diverse literature regarding the relationship between mathematical ability and success in physical chemistry, the role of mathematics in physical chemistry education requires further investigation. Additional research may reveal strategies that can support, or perhaps help resolve, the complex role of mathematics in physical chemistry.

2.1.2. Student and Instructor Perceptions of Physical Chemistry

A second challenge of physical chemistry education involves student and instructor perceptions about the challenging nature of physical chemistry. While instructors and students can have negative perceptions of physical chemistry, the root of these perceptions, and how these perceptions impact learning difficulties, varies between instructor and student (Sözbilir, 2004). Learning difficulties are divided into three categories: factors related to the student, factors related to the course, and factors related to the instructor.

For factors related to the student, the majority of students reported that lack of motivation or interest contribute to their learning difficulties. Instructors were in agreement, but also stated that differences in students' academic background and socioeconomic status play a role (Sözbilir, 2004). Instructors, unlike students, realized that each student brings a unique portfolio of abilities into the classroom, and effectively honoring the broad spectrum of abilities is a pedagogical challenge.

For factors related to the course, the majority of students reported that abstract concepts, overload of course content, and inconsistency between lecture and exams contributed to their learning difficulties (Sözbilir, 2004). Students were frustrated by the complexity and abundance of course topics, and felt that what they learned in class was not directly related to how they were assessed. Instructors, in contrast, stated that lack of curricular resources and overcrowded classrooms were to blame, and were frustrated with the lack of external help and the over–abundance of students (Sözbilir, 2004).

Finally, for factors related to the instructor, the majority of students reported that teacher–centered teaching contributed to their learning difficulties, while instructors stated that lack of time and support, overload of teaching, and lack of professional development opportunities were at fault (Sözbilir, 2004). Students believed that instructor dominated discourse added to the challenging nature of physical chemistry, while instructors believed that minimal support coupled with sizeable teaching loads were to blame.

Clearly, a disconnect exists between student and instructor perceptions of physical chemistry education. Negative perceptions of students revolved around aspects of the course that the instructor can control, including classroom discourse and assessment methods. In contrast, negative perceptions of instructors revolved around aspects of the course that the instructor cannot control, including diverse abilities of students and lack of support. To overcome learning difficulties in physical chemistry both the student and instructor perceptions need to be addressed. Given the numerous negative perceptions, further research is needed to investigate how to transform negative perceptions into productive teaching and learning strategies.

2.1.3. Pedagogical Content Knowledge of Physical Chemistry Instructors

A third challenge of physical chemistry education is minimal PCK of instructors. PCK is a blend of content knowledge and pedagogical knowledge and represents an educator's ability to adapt and convey concepts for learners (Shulman, 1986; Shulman, 1987). Various models of PCK exist, but Magnusson's model is often used in chemistry education because it was developed specifically for science instruction. In Magnusson's model of PCK, there are five components: orientation towards science teaching, knowledge of students' understanding of science, knowledge of science curricula, knowledge of instructional strategies in science, and knowledge of assessment in science (Magnusson, Krajcik & Borko, 1999). A more detailed literature review regarding PCK is presented in Chapter 5, but for now it is important to note that since instructors of physical chemistry are predominantly trained as researchers, frequently with minimal pedagogical training, they often have strong content knowledge but weaker pedagogical knowledge, and consequently weaker PCK.

Padilla and Van Driel (2011) investigated instructors' PCK and found that instructors had a stronger orientation towards teaching and a weaker knowledge of instructional strategies and assessment. This suggests that instructors can clearly articulate the goals of their course, but struggle to implement instructional strategies to achieve those goals, and struggle to create assessments to determine the degree to which those goals were achieved. Given the strong content knowledge of instructors, it is not surprising that they can clearly articulate the goals of the course; instructors often want students to learn what is historically relevant and what is applicable to modern research. In contrast, the weak PCK of instructors is evident through their difficulties to identify and implement effective teaching tactics, as well as their difficulties to identify both what and how to assess.

The role of mathematics, student and instructor perceptions, and the PCK of instructors represent three challenges related to the teaching and learning physical chemistry. Next, prior research regarding strategies to overcome the challenges of teaching and learning physical chemistry are addressed.

2.1.4. Strategies for Teaching and Learning Physical Chemistry

Various strategies regarding the teaching and learning of physical chemistry have been implemented to address the challenges identified in the previous subsections. To combat the challenging role of mathematics, some instructors provide a mathematics review at the beginning of the course to bring students up to speed with the necessary procedures and skills (Hahn & Polik, 2004). To dispel negative perceptions, some instructors use the first day of class to address, and hopefully reduce or eliminate, student concerns (Bruce, 2013). As an attempt to expand the PCK of instructors, some instructors have adopted context–based approaches to create meaningful learning experiences

(Stefani & Tsaparlis, 2009), such as creating analogies that model abstract physical chemistry concepts with everyday objects and events (Ma, 1996). Other instructors have implemented active learning strategies in order to increase student engagement (Towns & Grant, 1997; Hinde & Kovac, 2001). One study developed a game that reinforces the complexity of physical chemistry through an educational competition (Hoehn, Mack & Kais, 2014), while another study encouraged the process of learning, rather than the memorization of facts, through the development of macroscopic, particulate, and symbolic representations (Bruce, 2013). Furthermore, there is increased integration of computational software in physical chemistry courses, which provides and alternative way to calculate, visualize, and interpret problems in physical chemistry (Francis & Miles, 2002; Johnson & Engel, 2011).

These examples represent ongoing efforts to improve physical chemistry education. While the studies summarized above provide insight into the teaching and learning of physical chemistry, continued work can further transform the field of physical chemistry education research into a robust, prominent area of research.

2.2. Preview of Studies

The goal of Chapters 1 & 2 was to provide a rationale for research in physical chemistry education and to provide a literature background that broadly grounds the studies found in Chapters 3–5. A rationale and literature review specific to each study is included in Chapters 3–5. Chapter 3 investigates the current state of physical chemistry courses across the U.S. via a nationwide survey. Chapter 4 investigates characteristics of physical chemistry assessments including the format, type of knowledge, and type of cognitive processes of assessment questions. Chapter 5 uses instructor reflections to investigate the PCK of instructors including orientation towards teaching, knowledge of curriculum, knowledge of students' understanding, and knowledge of instructional strategies.

3. Nationwide Survey of the Undergraduate Physical Chemistry Course

3.1 Copyright Statement

Chapter 3 was adapted with permission from:

Fox, L. J., & Roehrig, G. H. (2015). Nationwide survey of the undergraduate physical chemistry course. *Journal of Chemical Education, 92*(9), 1456–1465.

3.2. Rationale

The purpose of this study was to develop a survey that examines the current state of undergraduate physical chemistry courses across the nation. The survey was administered to instructors of physical chemistry at American Chemical Society (ACS) certified institutions. The survey measured demographic information about the institutions, instructors teaching and research experience, the depth and breadth of course content, how content is delivered and assessed, and instructor beliefs about physical chemistry education. The goal of this study was to provide an awareness of the current state of physical chemistry courses across the United States (U.S.), as well as identify potential trends such as depth versus breadth of course content, learning goals versus assessment questions, degree of teacher preparation experience versus course delivery, and instructor beliefs about the challenging nature of physical chemistry education versus proposed solutions. Instructors may then use the survey data and subsequent trends to inform their pedagogical and curricular decisions.

This study expands prior research regarding the three main challenges of teaching and learning physical chemistry. The first challenge of physical chemistry education was the role of mathematics. This study aims to help rectify the unclear role of mathematics by investigating whether the goal of instructors is for students to develop a mathematical or conceptual understanding of specific topics, and how that goal is translated into instructional strategies and assessment materials. The second challenge of physical chemistry education was negative perceptions exhibited by both instructors and students. This study further investigates instructor perceptions by examining their beliefs regarding both the challenging nature of physical chemistry education, as well as how to combat such challenges. The third challenge of physical chemistry education was limited pedagogical content knowledge (PCK) of instructors. This study expands previous research regarding PCK by investigating relationships between components of PCK, such as the relationship between instructional strategies and assessment, and by investigating instructor proposed strategies to further develop their own PCK.

Ultimately, the purpose of this study was to address the following research question: What is the current state of physical chemistry education across the U.S.?

3.3. Literature Review

3.3.1. American Chemical Society Guidelines and Evaluation Procedures

The ACS has guidelines and evaluation procedures in place that chemistry departments must follow in order to achieve ACS certification, however such policy provides broad recommendations rather than specific standards (American Chemical Society Committee on Professional Training, 2015). For example, the ACS lists courses that students are required to take, but does not provide specific concepts or skills that students should master in each course. This gives instructors the responsibility to make decisions regarding which topics to cover or omit, as well as the depth versus breadth of various topics. Given this instructor freedom, what a student is exposed to in a physical chemistry course at one institution can vary considerably from what a student is exposed to at a different institution.

Another example of the broad ACS guidelines includes teaching strategies. The certification requirements state that faculty should use effective pedagogies, such as problem–based learning or inquiry–based learning, however there is no explanation for how to successfully implement these strategies (American Chemical Society Committee on Professional Training, 2015). Since instructors have the freedom to select any teaching approach, instructors often teach how they were taught. Such instructional strategies frequently involve instructor–dominated discourse.

A final example of the broad ACS guidelines involves assessment. The certification requirements do not provide any mandate for how to assess student understanding (American Chemical Society Committee on Professional Training, 2015).

The ACS Division of Chemical Education Examinations Institute has developed final, cumulative exams for each area of chemistry, including physical chemistry, however instructors are not required to use these exams (American Chemical Society Division of Chemical Education Examinations Institute, 2015). Many instructors create their own exams, but the ACS guidelines does not contain clear insight for the development of effective assessment materials.

In summary, the ACS guidelines contain broad standards regarding course content, pedagogy, and assessment, and these broad standards can be perceived and implemented in various ways by different instructors at different institutions. In physical chemistry education, this leads to widely varying course curriculum, instructional strategies, and assessment materials. Given this diversity, a survey is a useful method to investigate the potentially diverse physical chemistry courses across the country.

3.3.2. Survey Use in Chemical Education Research

The use of surveys is an efficient strategy to collect and analyze data for numerous characteristics of chemistry courses across the country. For example, in general chemistry a national survey was conducted to measure laboratory goals. Goals included overall research experience, group work and communication, data and error analysis, connection between lab and lecture, transferable skills, and writing (Bruck & Towns, 2013). The investigation of general chemistry laboratory goals from different institutions helped create measureable learning goals that could be used to assess and improve the quality of general chemistry laboratory instruction across the country.

A similar survey was conducted in the context of organic chemistry. This national survey explored the current state of organic chemistry laboratories by describing several aspects including the scale of the laboratory procedures, the types of chemical techniques used, the available instrumentation, the topics that were covered, how safety is presented, and how chemical waste is handled (Martin, Schmidt, Soniat & Martin, 2011). Since organic chemistry laboratories have changed considerably over time, the purpose of this survey was to explore the current state of organic chemistry laboratory education.

While the use of surveys is not uncommon in chemical education research, there are no recent surveys specific to physical chemistry education. The limited surveys that do focus on physical chemistry education were conducted over three decades ago, which suggested an ordering of topics (Physical Chemistry Subcommittee, 1973) and how many days to spend per topic (Cunningham & Hopkins, 1979).

Given the success of survey use in other chemistry disciplines, and the lack of recent surveys conducted for physical chemistry, this study developed a survey to provide a broad, yet detailed account, of the current state of physical chemistry education across the nation.

3.4. Methodology

A survey was developed to measure the depth and breadth of course content, how content is delivered and assessed, and the experiences and beliefs of instructors. The survey contained objective and open–ended questions (Appendix 1). A follow up survey was developed to further investigate the responses to the open–ended questions from the initial survey (Appendix 2). Responses to each survey were collected between March and May of 2014.

The survey was not developed within the context of an existing theoretical framework, but rather developed with the intent to be exploratory in nature. An established protocol was followed for the development of the survey (Cohen, Manion & Morrison, 2011). First, the objectives of the survey were defined and the survey questions were written to provide data in support of those objectives. The objectives are mentioned above and the corresponding survey questions can be found in Appendices 1 and 2. Second, the sample was selected, as described below. Third, the survey was piloted and fourth, the survey was administered.

All instructors of undergraduate physical chemistry at the 676 ACS certified institutions in the U.S. were invited to take the survey. When specific chemistry disciplines could be identified on the institution's website, emails were sent directly to instructors of physical chemistry. If instructors of physical chemistry could not be identified, emails were sent to the chair and administrative assistant of the department. A total of 348 instructors responded to the survey. Seventeen instructors were removed from the study for reasons including submitting a blank or primarily blank survey, not following survey directions, or self–identifying as solely a lab instructor. This left 331 surveys to be included in the analysis. The 331 participants represent a sample of physical chemistry instructors within the population of all physical chemistry instructors at ACS certified institutions in the country. Of the remaining 331 surveys, 187 instructors (56%) provided contact information, allowing responses to be associated with their institution. A follow up survey was sent to the 187 instructors who provided contact information, and 103 instructors (55%) responded.

Since the survey measured both quantitative and qualitative data, a mixed methods analysis was needed. For the quantitative data, descriptive and inferential statistics were computed using the statistical package, R (R Core Team, 2014). The qualitative data was analyzed via an inductive coding process. The text was initially examined via an open coding process, without predetermined codes, in order to allow themes to emerge. Once themes were established, the text was read again and the established themes were applied (Cohen, Manion & Morrison, 2011). Three researchers independently coded the data and achieved an inter rater reliability of 80% agreement. When there was disagreement for a code, the researchers discussed the code and came to a consensus.

3.5. Results

The results are divided into six subsections: participating institutions, participating instructors, course content, course delivery, course assessment, and instructor beliefs.

3.5.1. Participating Institutions

Colleges and universities represented in the survey include different types of institutions, institutions from different geographic regions, and institutions of different sizes, settings, and level of research activity (Table 3.1).

Table 3.1

Description of the Institutions (N = 187)

Institution Descriptor	*N*	Percent Frequency
Type of Institution		
Private	79	42%
Public	108	58%
Geographic Region		
West	23	12%
South	51	27%
Midwest	56	30%
Northeast	57	31%
Size		
Very Small	2	1%
Small	56	30%
Medium	59	32%
Large	70	37%
Setting		
Highly Residential	77	41%
Primarily Residential	63	34%
Primarily Nonresidential	47	25%
Highest Degree Offered and Level of Research Activity		
Baccalaureate	54	29%
Master’s	63	34%
Doctorate and Regular Research Activity	9	5%
Doctorate and High Research Activity	33	17%
Doctorate and Very High Research Activity	28	15%

The geographic regions include the West, South, Midwest, and Northeast, as defined by the U.S. Census Bureau (U.S. Census Bureau, 2014). The number of degree seeking students defines the size of the institution (The Carnegie Classification of Institutions of Higher Education, 2014). A very small institution has fewer than 1,000 students, a small institution has 1,000–2,999 students, a medium institution has 3,000–9,999 students, and a large institution has at least 10,000 students. The percent of students that live on campus and attend full time defines the setting of the institution (The Carnegie Classification of Institutions of Higher Education, 2014). For highly residential institutions at least 50% of students live on campus and at least 80% of students attend full time, for primarily residential institutions 25–49% of students live on campus and at least 50% of students attend full time, and for primarily nonresidential institutions fewer than 25% of students live on campus and fewer than 50% of students attend full time. The highest degree offered defines institutions as baccalaureate, master's or doctorate. For doctorate institutions, research and development expenditures and staff were analyzed via principal component analysis to define the level of research activity as regular, high, or very high (The Carnegie Classification of Institutions of Higher Education, 2014).

3.5.2. Participating Instructors

Instructors with varying years of teaching experience and research interests were represented in the survey (Table 3.2).

Table 3.2
Description of the Instructors (N = 331)

	N	Percent Frequency
Years of Teaching Experience		
1 to 5	54	16%
6 to 10	58	18%
11 to 15	65	20%
15 to 20	41	12%
At least 20	113	34%
Area of Research		
Experimental Chemistry	162	49%
Theoretical Chemistry	110	33%
Equally Experimental and Theoretical Chemistry	59	18%

On average, instructors reported that teaching responsibilities accounted for 55% of the workweek (*SD* = 21), research responsibilities accounted for 28% of the workweek (*SD* = 18), and other responsibilities accounted for 17% of the workweek (*SD* = 15). Regression analysis was performed to identify a relationship between how time was spent during the workweek with the institution's highest degree offered and level of research activity, resulting in significant group differences ($p < 0.001$). As the highest degree offered and level of research activity increased, the time spent performing teaching related responsibilities decreased and the time spent performing research related responsibilities increased (Figure 3.1).

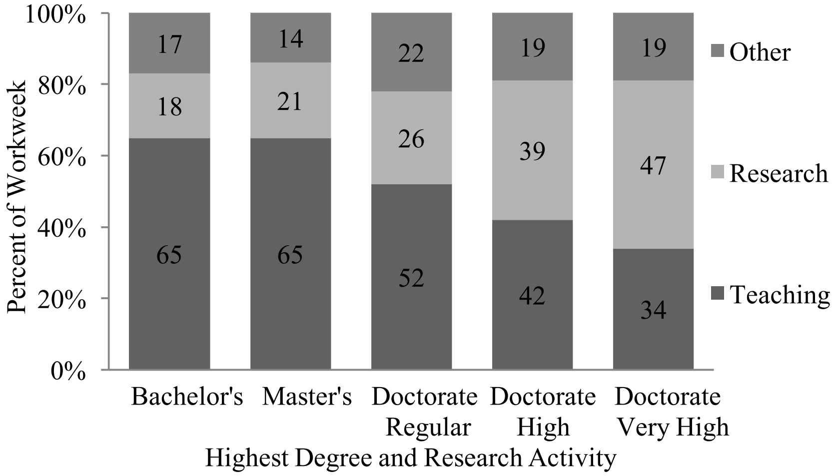

Figure 3.1. Barplot of how time is spent during the workweek for institutions with different highest degrees offered and levels of research activity. The average percent of the workweek accounted for by each responsibility is given in each segment of the bars.

Instructors described their teacher preparation experiences via an open–ended question. Responses were coded into four categories: great degree, moderate degree, minimal degree, and no teacher preparation experience. No teacher preparation was assigned when instructors left the question blank or stated that they had no teacher preparation experience. Minimal degree of teacher preparation was assigned when instructors mentioned workshops or conferences but did not explicitly state that chemical education research or professional development was the topic of the workshop or conference. Moderate degree of teacher preparation was assigned when instructors explicitly stated that they attended workshops or conferences regarding chemical education research or professional development. Great degree of teacher preparation was assigned when instructors led workshops or conferences regarding chemical education research or professional development, authored textbooks, or had a teaching license.

The majority of instructors had no teacher preparation experience or chose not to answer this open–ended question (52%) and very few instructors had a great degree of teacher preparation experience (4%). The remaining instructors were divided evenly between minimal (22%) and moderate (22%) degree of teacher preparation experience.

Of the instructors with a great degree of teacher preparation, 63% of those instructors were from a baccalaureate institution and the remaining 37% were form a master's institution. Of the instructors with no teacher preparation, 42% of those instructors were from a doctorate granting institution, 39% from a master's institution, and 19% from a baccalaureate institution. Thus, the majority of instructors with a great degree of teacher preparation experience were from a baccalaureate institution, while the majority of instructors with no degree of teacher preparation experiences were from a doctorate institution.

3.5.3. Physical Chemistry Course Content

Almost all institutions represented in the survey divide physical chemistry into one semester of thermodynamics and one semester of quantum mechanics. Less than 1% of the institutions offer one semester of introductory physical chemistry and one semester of advanced physical chemistry, where each semester covers both thermodynamics and quantum mechanics but the material is covered in greater detail during the second semester. For institutions that used trimesters, the thermodynamics and statistical mechanics trimesters corresponded to the semester of thermodynamics and the quantum mechanics trimester corresponded to the semester of quantum mechanics.

There was not a consistent trend for the ordering of the courses: 44% of the institutions required students to take thermodynamics first, 20% required students to take quantum mechanics first, and the remaining 36% allowed students to take the two semesters of physical chemistry in either order.

The three most commonly used textbooks were Atkins and de Paula (38%), McQuarrie and Simon (19%), and Engel and Reid (19%). The remaining institutions (24%) used 13 other textbooks, did not require a textbook, or offered multiple textbook options, each with a frequency less than 4%. Also, some instructors reported using mathematical software, such as Mathematica, however the survey did not directly measure the frequency of use for such technology.

Instructors were given a list of thermodynamics and quantum mechanics topics and asked if they covered each topic to a great degree, moderate degree, or not at all. If instructors did cover a topic to some degree, they then stated their goal for student understanding as mathematical, conceptual, or both. A mathematical understanding requires symbolic, procedural, and relational knowledge (Pirie & Kieren, 1989), while a conceptual understanding requires the ability to explain, compare, and defend information (Gordon & Gordon, 2006). For example, determining the solutions of a quadratic function requires a mathematical understanding, while explaining what those solutions represent in the context of the function requires a conceptual understanding.

Tables 3.3 and 3.4 show the percent frequencies for degree of coverage and goal for understanding of thermodynamics and quantum mechanics topics, respectively.

During the thermodynamics semester, solids and surface chemistry had the largest percent of no coverage (71%). Three other topics also had a large percent of no coverage: partition functions (34%), reaction dynamics (29%), and solid–liquid solutions (22%). At least 88% of the instructors reported some degree of coverage for all of the remaining topics. The most commonly covered topics, with at least 97% of instructors reporting some degree of coverage, include the first, second, and third laws of thermodynamics, Helmholtz and Gibbs energies, properties of gases, and chemical and phase equilibrium.

Table 3.3
Percent Frequency for Degree of Coverage and Goal for Understanding of Thermodynamics Topics, Reported by Physical Chemistry Instructors (N = 331)

Topic	Degree of Coverage (%)			Goal for Understanding (%)		
	Great	Moderate	None	Both	Conceptual	Mathematical
Second Law of Thermodynamics	90	10	0	95	3	2
First Law of Thermodynamics	88	12	0	94	3	3
Helmholtz and Gibbs Energies	86	14	0	93	3	4
Chemical Equilibria	73	25	2	94	5	1
Rate Laws	69	24	7	91	4	5
Third Law of Thermodynamics	65	35	0	82	16	2
Properties of Gases	63	36	1	93	4	3
Phase Equilibria	57	40	3	74	24	2
Reaction Mechanisms	47	42	11	74	25	1
Kinetic Theory of Gases	46	44	10	76	21	3
Boltzmann Factor	36	54	10	76	18	6
Liquid–Liquid Solutions	35	53	12	69	30	1
Partition Functions	30	36	34	72	22	6
Solid–Liquid Solutions	21	57	22	63	36	1
Reaction Dynamics	19	52	29	52	46	2
Solids and Surface Chemistry	2	27	71	43	56	1

During the quantum mechanics semester, two topics had the largest percent of no coverage: symmetry and group theory (47%) and laser spectroscopy (41%). Two other topics also had a large percent of no coverage: computational methods (25%) and classical mechanics (24%). At least 87% of the instructors reported some degree of coverage for all of the remaining topics. The most commonly covered topics, with at least 99% of instructors reporting some degree of coverage, include the postulates of quantum mechanics, particle in a box, harmonic oscillator, rigid rotator and the hydrogen atom.

Table 3.4
Percent Frequency for Degree of Coverage and Goal for Understanding of Quantum Mechanics Topics, Reported by Physical Chemistry Instructors (N = 331)

Topic	Degree of Coverage (%)			Goal for Understanding (%)		
	Great	Moderate	None	Both	Conceptual	Mathematical
Particle in a Box	91	9	0	95	1	4
Harmonic Oscillator	86	14	0	89	7	4
Hydrogen Atom	84	15	1	89	7	4
Rigid Rotator	79	20	1	86	9	5
Postulates	67	32	1	70	27	3
Diatomic Molecules	66	31	3	73	25	2
Molecular Spectroscopy	52	43	5	69	28	3
Multi Electron Atoms	48	48	4	55	43	2
Free Particle	39	49	12	74	21	5
Approximation Methods	35	55	10	61	33	6
Polyatomic Molecules	28	59	13	50	50	0
Symmetry and Group Theory	17	36	47	60	38	2
History of Quantum Mechanics	14	78	8	33	66	1
Computational Methods	12	63	25	40	56	4
Laser Spectroscopy	10	49	41	37	63	0
Classical Mechanics	8	68	24	68	26	6

Most instructors reported the goal of developing both a conceptual and mathematical understanding. For each thermodynamics and quantum mechanics topic at least 43% and 33% of the instructors, respectively, reported the goal of developing both a conceptual and mathematical understanding. As the percent frequency for great degree of coverage increased, the percent frequency for both a mathematical and conceptual understanding approximately increased. In other words, for topics covered by a greater percent of instructors, both a mathematical and conceptual understanding was preferred. In contrast, as the percent frequency for great degree of coverage decreased, the percent frequency for a pure conceptual understanding approximately increased. In other words, for topics covered by a smaller percent of instructors, a pure conceptual understanding was preferred. A pure mathematical understanding was not very common; for each thermodynamics and quantum mechanics topic less than 7% of instructors reported the goal of developing a pure mathematical understanding.

To better understand the relationship between the depth and breadth of topics covered in thermodynamics and quantum mechanics, instructors were given a depth score and a breadth score. The breadth score represents the number of topics that were covered, and was calculated as the percent of topics that instructors reported covering to either a great or moderate degree. The depth score represents the degree to which each topic was covered, and was calculated as the weighted average of topics that instructors reported covering, where a great degree represents covering the topic twice as in depth as a moderate degree. In other words, a topic covered to a great degree is defined as 100% coverage, while a topic covered to a moderate degree is defined as 50% coverage.

If time was a limiting factor of what was taught in a physical chemistry course, then as the breadth of topics increased the depth should decrease. This was not the case, however, given the instructor–reported data. For thermodynamics topics, as the breadth of topics increased, the depth of topics remained constant. This means that regardless of how many topics an instructor covered the depth of coverage remained the same. For quantum mechanics, as the breadth of topics increased, the depth of topics also increased.

This means that instructors who covered more topics also covered those topics more in depth.

To further understand the relationship between depth and breadth of topics, a goal for understanding score was calculated as the difference between the number of topics with a goal for conceptual and mathematical understanding. When the understanding score was added as a predictor to the relationship between the depth and breadth of topics, there was no change in the relationship for both thermodynamics and quantum mechanics topics. In other words, regardless of a net goal for conceptual or mathematical understanding, the relationship between depth and breadth remained the same.

To better understand why the depth, breadth, and goal for understanding of thermodynamics and quantum mechanics topics varied among instructors, the data in Tables 3.3 and 3.4 were analyzed against several predictors including years of teaching experience, research area, time dedicated to teaching responsibilities, degree of teacher preparation, selected textbook, course delivery, and highest degree offered by the institution. This allowed Tables 3.3 and 3.4 to be stratified by, for example, instructors who conduct theoretical versus experimental research, or instructors who use Atkins and de Paula versus McQuarrie and Simon versus Engel and Reid. While the degree of coverage and goal for understanding of some topics were significantly different based on the different values of the predictors above, the minimal number of significant differences makes it challenging to identify any clear patterns. Thus, none of the predictors above can clearly explain the variation in the depth, breadth, and goal for understanding of thermodynamics and quantum mechanics topics.

3.5.4. Physical Chemistry Course Delivery

Instructors were asked to describe their classroom environment as instructor–centered, student–centered, or both (Table 3.5). Instructor–centered discourse is defined as a classroom environment where the instructor speaks more often than the students, for example a traditional lecture. Student–centered discourse is defined as a classroom environment where the students speak more often than the instructor, for example students teaching and learning from each other in small groups. The majority of instructors (79%) reported delivering course content in an instructor–centered environment and very few instructors (2%) reported delivering course content in a student–centered environment.

Table 3.5

Description of Physical Chemistry Course Delivery (N = 331)

Type of Classroom Environment	*N*	Percent Frequency
Instructor–Centered	262	79%
Equally Instructor and Student–Centered	61	19%
Student–Centered	8	2%

Of the instructors who reported delivering course content in a student–centered environment, 80% of those instructors were from a baccalaureate institution and the remaining 20% were from a master's institution. In contrast, of the instructors who reported delivering course content in an instructor–centered environment, 41% of those instructors were from a doctorate institution, 36% were form a master's institution and 23% were form a baccalaureate institution. Thus, the majority of instructors who adopt student–centered approaches were from a baccalaureate institution, while the majority of instructors who adopt instructor–centered approaches were form a doctorate institution.

Additionally, 88% of instructors with no teacher preparation experience and 84% of instructors with a great degree of teacher preparation experience, each reported delivering content in an instructor–centered environment. This suggests that degree of teacher preparation experience does not meaningfully impact course delivery.

3.5.5. Physical Chemistry Course Assessment

Instructors were asked to describe their physical chemistry assessment questions as objective or subjective and as mathematical or conceptual (Table 3.6). Objective questions were defined as questions that ask students to select the correct answer from a given set of possible answers, for example multiple–choice, true or false, and matching questions. Subjective questions were defined as questions that ask students to develop the correct answer without a set of possible answers to choose from, for example open–ended essays or problems. Mathematical questions were defined as questions that require students to use more procedures and symbolic notation than words to develop the correct answer, while conceptual questions were defined as questions that require students to use more words than procedures and symbolic notation.

On average, instructors reported giving more assessment questions that were subjective and mathematical in nature. When assessment questions from baccalaureate, master's and doctorate institutions were compared, any variation among the different types of institutions was within one standard deviation of the mean. Thus, there is no significant difference between types of assessment questions among institutions with different highest degrees offered.

Table 3.6

Description of Physical Chemistry Assessments (N = 331)

Assessment Descriptor	Mean Percent	*SD*
Format		
Subjective	87%	19
Objective	13%	18
Type of Knowledge		
Mathematical	62%	17
Conceptual	38%	17

It is interesting to note that while instructors reported, on average, that their assessments consisted of more mathematical questions, the majority of instructors reported the goal of developing both a conceptual and mathematical understanding, or a pure conceptual understanding. To better understand this discrepancy, instructors were divided into groups based on an assessment score and an understanding score (Table 3.7). The assessment score is the difference between the number of mathematical and conceptual questions instructors reported asking on their exams. The understanding score is the difference between the number of topics that instructors reported the goal for developing a pure mathematical understanding and a pure conceptual understanding.

Table 3.7

Comparison of Preferred Type of Assessment Questions and Goal for Understanding (N = 331)

Majority (%)	Type of Assessment Question		
Goal for Understanding	Mathematical	Conceptual	Equal
Mathematical	3	1	1
Conceptual	52	9	18
Equal	11	2	3

Only 15% of instructors had agreement between their assessment questions and goal for understanding. The remaining 85% of instructors had disagreement between their assessment questions and goal for understanding. The largest discrepancy (52%) occurred for instructors who reported the goal of developing a conceptual understanding but also reported giving a majority of mathematical questions. Clearly a disconnect exists between instructor reported learning goals and assessment questions.

Instructors also reported their average final course grade distributions (Table 3.8). When final course grades from baccalaureate, master's and doctorate institutions were compared, any variation was within one standard deviation of the mean. Thus, there was no significant difference between final course grade distributions among institutions with different highest degrees offered. Also, when the final course grades for student–centered and instructor–centered teaching strategies were compared, any variation was within one standard deviation of the mean. Thus, there was no significant difference between final course grade distributions among different course delivery tactics.

Table 3.8
Description of Physical Chemistry Final Course Grade Distributions (N = 331)

Final Course Grade	Mean Percent	*SD*
A	21%	11
B	36%	13
C	28%	12
D	8%	7
F	4%	5
Withdrawal	3%	5

3.5.6. Beliefs of Physical Chemistry Instructors

Instructors were asked how similar they believe their physical chemistry course is compared to other physical chemistry courses at ACS certified institutions (Table 3.9). Instructors were also asked how similar they think physical chemistry courses at ACS certified institutions should be (Table 3.9). The majority of instructors reported that their course is, and should be, somewhat similar to other physical chemistry courses.

Table 3.9

Instructor Beliefs (N = 103) of How Their Physical Chemistry Course Does Compare, and Should Compare, to Other Physical Chemistry Courses at ACS Certified Institutions

	N	Percent Frequency
My physical chemistry course is _____ compared to other physical chemistry courses across the U.S.		
Very Similar	32	31%
Somewhat Similar	51	50%
Somewhat Different	16	15%
Very Different	4	4%
Physical chemistry courses across the U.S. should be _____		
Very Similar	19	18%
Somewhat Similar	69	67%
Somewhat Different	14	14%
Very Different	1	1%

Before investigating the challenges of and proposed strategies for physical chemistry education, it is important to note how instructors view the role of students in the teaching and learning of physical chemistry. The majority of instructors reported that the instructor and students are equally responsible (78%) for developing students' understanding of physical chemistry. Another 21% of instructors reported that students are mostly responsible for developing their own understanding and that the instructor is somewhat responsible. Only 1% of instructors reported that the instructor is mostly responsible for developing students' understanding and that the students are somewhat responsible. No instructors reported that either the students or the instructor are completely responsible for developing students' understanding of physical chemistry.

Instructors were asked to explain why students may struggle to understand physical chemistry. In order of decreasing frequency, instructors reported that students struggle: because they lack the necessary mathematics background (61%), to make connections between the concepts and mathematics (33%), because they do not put forth the necessary effort (18%), to understand the concepts (13%), because they lack the necessary physics background (6%), and because physical chemistry is a challenging course (3%).

Instructors were also asked to explain how student understanding of physical chemistry may be improved. In order of decreasing frequency, instructors reported the following: instructors need to modify their teaching strategies (23%), students need to put forth more effort (10%), better resources, such as textbooks and visualization tools, are needed (10%), and more relevant examples and applications are needed (8%).

To further investigate why students may struggle to understand physical chemistry and how student understanding may be improved, instructors ranked the reasons listed above in order of relevance. Average rankings were computed, where a larger average represents a more relevant statement (Table 3.10).

Table 3.10

Instructor Rankings (N = 103) of Why Students May Struggle to Understand Physical Chemistry and How Student Understanding May Be Improved

Instructor Belief Statements	Rating						
	1	2	3	4	5	6	
	Percent Frequency						Mean
Students struggle:							
To make connections between concepts and mathematics	3	2	9	24	26	39	4.80
Because they lack the necessary math background	1	14	24	20	21	23	4.12
To understand the concepts	10	22	14	24	25	8	3.54
Because physical chemistry is a challenging course	31	13	18	10	12	19	3.16
Because they do not put forth the necessary effort	25	22	18	19	8	11	2.96
Because they lack the necessary physics background	33	30	20	6	11	3	2.43
Student understanding may be improved if:							
Students put forth more effort	20	22	32	29			2.68
More relevant examples and applications are available	20	25	32	26			2.62
Instructors modified their teaching strategies	16	39	21	27			2.57
Better resources were available	47	18	17	21			2.12

There was greater variation in the rankings for reasons why students struggle (*SD* = 0.85) and less variation in the rankings for how student understanding may be improved (*SD* = 0.26). This suggests that instructors are in stronger agreement about the challenges of physical chemistry education and in weaker agreement about how to overcome those challenges.

Finally, instructors were asked why it may be challenging to try different teaching strategies. In order of decreasing frequency, instructors reported the following as a challenge: lack of time (89%), lack of resources (51%), lack of professional development opportunities (39%), resistance from colleagues and department heads (22%), and lack of interest (17%). Only 3% of instructors reported that there are no challenges in trying different teaching strategies.

3.6. Discussion

Given the large response rate (*N* = 331), that the institutions represented in the survey are of different types, demographics, and research activity, and that the instructors represented in the survey have different years of teaching experience, research areas, and teacher preparation experience, the results of the survey represent a variety of physical chemistry courses across the country. There are inherent limitations to data collected via surveys, however. First, given that the data is self–reported, there is no guarantee that instructors provided complete, accurate, and honest answers. Second, the data does not include the perspective of every instructor of physical chemistry, nor every department of chemistry at ACS certified institutions, which may make significant results less reliable if the instructors who elected to respond to the survey are not representative of all instructors. Finally, the results of this study only represent the perspective of instructors, not students. This decision was purposeful, however, since instructors often receive feedback from their students but rarely receive information from other instructors across the nation. Despite these limitations, the results of this survey show eight clear themes in physical chemistry education.

The first theme is the relationship between time allocated to teaching and research related responsibilities and the level of research activity of the institution: as the level of research activity increased, the time allocated to teaching related responsibilities decreased and the time allocated to research related responsibilities increased. While this trend may seem obvious, there are broader implications. When more time was dedicated to teaching, there was a greater proportion of instructors who reported creating student–centered learning environments, which occurred more frequently at baccalaureate institutions. Also, when more time was dedicated to teaching there was no change in final course grades, suggesting that final course grades were not influenced by the division of teaching and research responsibilities, as well as course delivery or type of institution.

The second theme is the lack of a relationship between degree of teacher preparation experience and course delivery. While a majority of instructors reported having no teacher preparation experience, approximately the same percent of instructors who had no teacher preparation experience and a great degree of teacher preparation experience reported delivering content in an instructor–centered environment. Also, since there is no relationship between course delivery and final course grades, there is no relationship between degree of teacher preparation experience and final course grades. Thus, increased teacher preparation experience may not translate into modified or improved teaching practices.

The third theme is the relationship between the depth and breadth of course content. If time was a limiting factor, as the breadth of topics increased the depth of topics should decrease. This, however, was not observed in the results of the survey. For thermodynamics topics, as the breadth of topics increased, the depth of topics remained constant. For quantum mechanics topics, as the breadth of topics increased, the depth of topics also increased. Thus, some thermodynamics instructors are covering additional topics without losing the depth of coverage, and some quantum mechanics instructors are covering additional topics while simultaneously covering topics in greater detail.

The fourth theme is the variation of depth, breadth, and goal for understanding of thermodynamics and quantum mechanics topics. The thermodynamics and quantum mechanics topics that were covered by a large percent of instructors were not surprising, given their historical prevalence, but the topics covered by fewer instructors are noteworthy. Several predictors including years of teaching experience, research area, time dedicated to teaching responsibilities, degree of teacher preparation, selected textbook, course delivery and highest degree offered by the institution were investigated, but none of those parameters could clearly explain variation in course content or goal for understanding. Thus, there is no distinct factor, included in the survey, that influenced the variation in physical chemistry curriculum.

The fifth theme is that while instructors reported giving more mathematical questions on assessments, the majority of instructors reported the goal for developing a conceptual and mathematical understanding, or purely a conceptual understanding, of thermodynamics and quantum mechanics topics. Thus, there is a discrepancy between reported learning goals and how instructors assess students' understanding.

The sixth theme is the consistency of final course grade distributions. There was no significant variation in grade distribution based on research activity of the institution, and on average, 85% of students pass physical chemistry with an A, B, or C. The high pass rate may suggest grade inflation, but the approximate equal percent of each passing grade may suggest that there is no grade inflation. While instructors reported that 85% of students pass the course, this study did not measure if instructors or students believed that sufficient comprehension of physical chemistry concepts and skills was attained, and therefore passing the class was warranted. Also, there may be variation in the difficulty of exam questions between different instructors, which may be partially due to the variation in depth and breadth of topics and types of assessment questions. Such variation makes it challenging to compare final grade distributions among different instructors.

The seventh theme represents instructors' beliefs regarding how similar physical chemistry courses are and should be. The majority of instructors reported that their physical chemistry course is and should be similar to physical chemistry courses across the country. This bodes well for the similarities among course content, delivery, and assessment evident in the results of this study, but raises questions and concerns for all of the variation, diversity, and contradictions also evident in this study.

The eighth theme is the relationship between instructor beliefs about why students may struggle to understand physical chemistry and how student understanding may be improved. There was larger variation when instructors ranked reasons for why students struggle, compared to the variation when instructors ranked strategies that may overcome students' difficulties. This suggests that instructors were in stronger agreement regarding the challenges of physical chemistry education and in weaker agreement regarding potential strategies to overcome those challenges. Since instructors did not unanimously agree on strategies to better support students, it is not surprising that instructors face several challenges in their efforts to develop improved pedagogical practices. Instructors reported that the top three reasons why it is challenging to implement new teaching approaches are lack of time, resources, and professional development opportunities. To honor instructors' limited time, researchers of chemical education should collaborate with instructors of physical chemistry by providing effective resources and professional development opportunities designed to improve the PCK of instructors.

3.7. Implications for Teaching

Based on the themes presented in the discussion, there are two guiding questions that instructors of physical chemistry should consider as they move forward with their teaching.

First, how do instructors translate learning goals into assessment questions? Before assessments are created, instructors should be conscious of their learning goals. This includes considering the advantages or disadvantages of covering a larger breadth of topics or covering topics more in depth, as well as identifying what topics require a conceptual understanding, mathematical understanding, or both. Once the learning goals are made explicit, all assessment questions should directly align with the learning goals. This implication led to the second study of this dissertation, which is an in–depth investigation of physical chemistry assessments. The purpose of the second study was to provide an awareness of the current state of physical chemistry assessments, and to further investigate the relationship between instructors' learning goals and how student understanding is assessed.

Second, how does the PCK of instructors translate into course content and teaching strategies? Instructors should be aware of how their PCK impacts their pedagogical and curricular decisions. Instructors should also be self–motivated to further develop their PCK in order to improve their instruction. To aid instructors in this process of personal reflection and growth, support should be provided. Support can come from fellow colleagues, leaders within the institution, educational research, curricular and assessment resources, and professional development opportunities. This implication led to the third study of this dissertation, which is an analysis of instructor reflections on the teaching and learning of physical chemistry. The purpose of the third study was to provide a rich description of the PCK of instructors by eliciting instructors' orientation towards teaching, knowledge of curriculum, knowledge of students' understanding, and knowledge of instructional strategies through a reflection protocol.

4. An Investigation of Physical Chemistry Assessments

4.1. Rationale

The nationwide survey of physical chemistry described in Chapter 3 found a discrepancy between instructor reported learning goals and assessment materials. While most instructors reported the goal for students to develop a conceptual understanding, their assessments contained primarily mathematical questions. This may suggest that there is a contradiction between learning goals and assessment questions, or that instructors are unaware of how their pedagogical decisions impact the characteristics of their assessments. To further investigate assessment practices, a detailed analysis of instructor–written assessments is needed.

The purpose of this study is to investigate the current state of physical chemistry assessments within colleges and universities across the country. Characteristics of assessment questions analyzed include the format, type of knowledge elicited, and type cognitive process required. The goal of this analysis is to provide a rich description of the current state of physical chemistry assessments across the United States (U.S.), using quantitative methods to provide an overview, as well as qualitative methods to describe specific cases.

This study expands prior research regarding the three main challenges of teaching and learning physical chemistry. The first challenge of physical chemistry education was the role of mathematics. Recall that prior research investigated the relationship between students' prerequisite mathematical ability and success in physical chemistry (Hahn & Polik, 2004; Nicoll & Francisco, 2001; Derrick & Derrick, 2002). This study shifts the focus from prerequisite mathematical ability to how mathematics is used in physical chemistry assessments. The second challenge of physical chemistry education was the negative perceptions exhibited by both instructors and students. Recall that both students and instructors had negative perceptions of physical chemistry, but the root of those perceptions varied between students and instructors (Sözbilir, 2004). While this study does not directly address negative perceptions, it may help instructors realize how their perceptions of physical chemistry education motivate their assessment practices. The third challenge of physical chemistry education was the limited pedagogical content knowledge (PCK) of instructors. Recall that instructors, who are primarily trained as researchers and not educators, often have strong content knowledge but weaker pedagogical knowledge, and consequently weaker PCK (Padilla & Van Driel, 2011). This study targets the assessment component of PCK, instructors' knowledge of assessments, and focuses on how, rather than which, concepts and skills are assessed.

Ultimately, the purpose of this study was to address the following research question: What is current state instructor–written of physical chemistry assessments?

4.2. Literature Review

4.2.1. Analysis of American Chemical Society Exams

The American Chemical Society (ACS) Division of Chemical Education Examinations Institute has developed exams for numerous areas of chemistry including general, organic, inorganic, analytical, and physical chemistry (American Chemical Society Division of Chemical Education Examinations Institute, 2015). ACS exams are comprised completely of multiple–choice questions, and assess students conceptual and procedural understanding. Instructors are not required to give ACS exams, including instructors employed as ACS certified chemistry departments. Instead, instructors may elect to give ACS exams as a means to compare current and past students, or students of the same department but who have different instructors. The ACS also publishes national exam statistics which allow instructors to make external comparisons and examine how their students perform against the national norm.

Research regarding the ACS physical chemistry exams is lacking, but research regarding the ACS general chemistry and organic chemistry exams is prevalent. For example, one study investigated two decades of the ACS general chemistry exams to provide a description of the content, visualization, and type of knowledge present in the exam questions (Luxford et al., 2015). In terms of content, topics that were tested at a higher frequency include atoms, intermolecular forces, and reactions, while topics tested at a lower frequency include bonding, kinetics, and experiments. About half of the questions contained a visual component, with the two most common visuals being reactions and tables. Other visuals that were found in roughly 10% of questions, include graphs, structures, particulate nature of matter, pictures, and equations. Knowledge type was used to categorize questions that required recall, algorithmic processes, or conceptual thinking. About 10% of questions required recall, 30% required algorithmic processes, and 60% required conceptual thinking.

A second study investigated six decades of the ACS organic chemistry exams. Like the study of ACS general chemistry exams, the investigation of ACS organic chemistry exams also examined content, visualization, and type of knowledge present in the exam questions (Raker & Holme, 2013). For content, topics with a great degree of coverage included substitution and elimination reactions, and as new techniques were developed there was a shift towards fewer questions regarding qualitative analysis and more questions regarding spectroscopy. More than 90% of the exam questions contained some form of visualization, with chemical structures being the most common form of visualization. For type of knowledge, there has been a shift to more conceptual thinking and less recall. In fact, today the ACS organic chemistry exams are about 95% conceptual thinking, 4% algorithmic, and 1% recall.

The purpose of these two studies was to provide a historical summary of ACS chemistry exams, but further implications for teaching should be considered. While a historical perspective of ACS exams is beneficial in observing the development of chemical education over time, such analysis does not dictate what happens in the classroom. To continually strive for outstanding undergraduate chemistry education, the focus should shift from what and how topics are being assessed, to why those assessment choices were selected. For example, the advantages and challenges of different assessment strategies should be discussed. Additionally, instructors should create alignment between learning goals and assessment materials so that students' mastery of learning goals can be demonstrated via the assessment materials.

4.2.2. Factual, Conceptual, and Procedural Knowledge

One key assessment characteristic analyzed in the ACS general and organic chemistry exams was type of knowledge. In this study of physical chemistry assessments, knowledge is categorized into three types: factual, conceptual, and procedural. These three categories were selected so that the type of knowledge used in instructor–written physical chemistry exams can be compared to the type of knowledge investigated in ACS exams, where factual knowledge corresponds to recall, conceptual knowledge corresponds to conceptual thinking, and procedural knowledge corresponds to algorithmic processes (Luxford et al., 2015; Raker & Holme, 2013). Definitions and examples of factual, conceptual, and procedural knowledge are below.

Factual knowledge is defined as "the basic elements that students must know to be acquainted with a discipline or solve problems in it" (Krathwohl, 2002, p. 214). Examples of factual knowledge include knowledge of terminology, specific details, and elements. In physical chemistry, stating that a wave function must be continuous requires factual knowledge. Factual knowledge in this study corresponds to recall items found in the ACS exams studies (Luxford et al., 2015; Raker & Holme, 2013).

Conceptual knowledge is defined as "the interrelationships among the basic elements within a larger structure that enables them to function together" (Krathwohl, 2002, p. 214). Examples of conceptual knowledge include knowledge of classifications and categories, principles and generalizations, and theories, models, and structures. In physical chemistry, describing what it means for a wave function to be continuous and explaining why a wave function must be continuous requires conceptual knowledge. Conceptual knowledge in this study corresponds to conceptual thinking items found in the ACS exams studies (Luxford et al., 2015; Raker & Holme, 2013).

Procedural knowledge is defined as "how to do something; methods of inquiry, and criteria for using skills, algorithms, techniques, and methods" (Krathwohl, 2002, p. 214). Examples of procedural knowledge include knowledge of subject–specific skills and algorithms, techniques and methods, and criteria for determining when to use appropriate procedures. In physical chemistry, proving mathematically that a wave function is continuous requires procedural knowledge. Procedural knowledge in this study corresponds to algorithmic process items found in the ACS exams studies (Luxford et al., 2015; Raker & Holme, 2013).

4.2.3. Bloom's Taxonomy of Cognitive Processes

While factual, conceptual, and procedural knowledge are used to categorize type of knowledge, Bloom's taxonomy describes how different types of knowledge are used. Bloom's taxonomy, which is a framework for categorizing educational goals, was developed so that specific targets could be used to create productive learning experiences (Bloom, 1956). Bloom's taxonomy consists of three domains: cognitive, affective, and psychomotor. The cognitive domain involves knowledge, the affective domain involves emotions and attitudes, and the psychomotor domain involves physical skills and faculties. Since physical chemistry exams predominantly assess the cognitive domain, the cognitive domain of Bloom's taxonomy was used in this study to examine the type of cognitive processes evident in assessment questions.

The cognitive domain of Bloom's taxonomy, in a revised version, is divided into six processes: remember, understand, apply, analyze, evaluate, and create (Krathwohl, 2002). These processes are organized from less complex to more complex. Traditional education often emphasizes simpler cognitive processes, while reformed education strives to incorporate the more complex cognitive processes. A detailed description of Bloom's taxonomy is found in Table 4.1.

Table 4.1
A Description of Bloom's Taxonomy

Cognitive Process	Definition	Synonyms
Remember	Retrieving relevant knowledge from long–term memory	Recognize Recall
Understand	Determining the meaning of instructional messages, including oral, written, and graphic communication	Interpret Exemplify Classify Infer Compare Explain
Apply	Carrying out or using a procedure in a given situation	Execute Implement
Analyze	Breaking material into its constituent parts and detecting how the parts relate to one another and to an overall structure or purpose	Differentiate Organize Attribute
Evaluate	Making judgments based on criteria and standards	Check Critique
Create	Putting elements together to form a novel, coherent whole or make an original product	Generate Plan Produce

Bloom's taxonomy is an extension of the types of knowledge described in the previous section. Type of knowledge is used to categorize knowledge, while the cognitive processes of Bloom's taxonomy are used to categorize how knowledge is used. In other words, type of knowledge describes what knowledge is present, while Bloom's taxonomy describes how knowledge is used. This is further evident in the predominant use of nouns to describe the type of knowledge, and in contrast the predominant use of verbs to describe the cognitive processes of Bloom's taxonomy.

Bloom's taxonomy has been used in prior research to analyze science assessments. For example, in organic chemistry one study found that instructors often teach towards the lower end of Bloom's taxonomy but assess at the higher end, and provide minimal support to help students ascend Bloom's taxonomy and develop a deeper understanding of concepts (Pungente & Badger, 2003). To counter this difficulty, Pungente and Badger (2003) recommend that instructors make explicit connections in their teaching. For example, connections between the fundamental principles of general and organic chemistry, or the connections between the concepts and reactions of organic chemistry, should be made explicit by instructors. Students can then use those connections to develop a deeper understanding of topics and ascend Bloom's taxonomy.

Another example of Bloom's taxonomy is found in general biology. Crowe, Dirks & Wenderoth (2008) developed a Blooming Biology Tool (BBT) to help instructors better align their assessment materials and instructional strategies. The BBT contained examples of assessment questions for each level of Bloom's taxonomy, as well as how the questions could be formatted. Additionally, the BBT contained examples of classroom activities that could be implemented to develop students' understanding at each level of Bloom's Taxonomy. The BBT was found to be helpful in exposing current characteristics of assessment and instructional practices, as well as helping instructors create better alignment between what and how they teach with what and how they assess.

4.2.4. Instructors' Knowledge of Assessment

In addition to prior work regarding the ACS general and organic chemistry exams, as well as type of knowledge and type of cognitive processes, previous research has also investigated instructors' knowledge of assessment. For example, two studies investigated instructors' knowledge of assessment terminology (Emenike, Raker & Holme, 2013; Raker, Emenike & Holme, 2013). Likert–scale statements were used to measure instructors' familiarity with different types of assessment, including formative and summative, as well as how to measure the validity, reliability, or difficulty of questions. The results showed an approximate uniform distribution between completely unfamiliar to completely familiar for many of the assessment terminologies, suggesting that there is no majority group of instructors who have a certain understanding of assessment terminology. The purpose of these studies was to investigate focus areas for professional development opportunities, but given the wide range of responses, a more comprehensive support for instructors and their knowledge of assessment may be needed.

In addition to investigating instructors' knowledge of assessment terminology, prior research has also investigated the motivations behind assessment practices. One study found that instructors' assessment practices were primarily motivated by factors regarding external accreditation and internal decisions (Emenike, Schroeder, Murphy & Holme, 2013). When instructors were asked about their role in the development or transformation of assessment practices, the majority of instructors reported that they participate by providing class data, very few reported that they take charge in making changes. Several challenges of assessment efforts include lack of time, convincing instructors to participate, and transforming efforts into productive changes. Thus, not only do instructors need help expanding their knowledge of assessment, but additional support is needed to help instructors transform new knowledge into action.

Given the current state of instructors' knowledge of assessment, additional research and collaborative efforts between researchers and educators are needed to help instructors develop assessment materials. This study broadens prior research through an investigation of instructors' knowledge of assessment in physical chemistry.

4.3. Methodology

This study adopted a mixed methods approach, which utilized both quantitative and qualitative methodologies in order to obtain a more comprehensive understanding of physical chemistry assessments (Cohen, Manion & Morrison, 2011). For the quantitative approach, descriptive and inferential statistics were used to provide an overview of assessment characteristics across all participants. For the qualitative approach, the assessments of select instructors, who represent either a trend or an anomaly, were analyzed to provide a rich description of assessment practices.

Twenty-seven instructors provided their physical chemistry assessments for this study. These 27 instructors also participated in the nationwide survey and volunteered to share their assessment materials. At the request of the researchers, instructors provided their midterm exams and final exams, which were summative in nature. Instructors shared assessments for either thermodynamics, quantum mechanics, or both, depending on what courses they teach. Thirteen instructors provided assessments for both thermodynamics and quantum mechanics, seven instructors provided assessments for thermodynamics only, and seven instructors provided assessments for quantum mechanics only. In total, the assessments span the entire semester of 20 thermodynamics courses and 20 quantum mechanics courses. The instructors who shared their assessment materials are roughly representative of the instructors who responded to the nationwide survey, given the frequencies of various institutional characteristics (Table 4.2).

Table 4.2

Description of the Participating Instructors (N = 27)

	Study 2: Assessment Analysis		Study 1: Nationwide Survey	
	N	Percent Frequency	*N*	Percent Frequency
Type of Institution				
Private	9	33%	79	42%
Public	18	67%	108	58%
Geographic Region				
West	2	8%	23	12%
South	6	22%	51	27%
Midwest	10	37%	56	30%
Northeast	9	33%	57	31%
Size				
Small	8	30%	58	31%
Medium	10	37%	59	32%
Large	9	33%	70	37%
Setting				
Highly Residential	10	37%	77	41%
Primarily Residential	11	41%	63	34%
Primarily Nonresidential	6	22%	47	25%
Highest Degree Offered				
Bachelor’s	8	30%	54	29%
Master’s	10	37%	63	34%
Doctorate	9	33%	70	37%

Each assessment question was given three codes based on format, type of knowledge, and type of cognitive process. Codes for question format were divided into objective questions, which include multiple–choice, true or false, and matching, and subjective questions, which include short answer and open–ended problems. The objective and subjective definitions of this study align with the objective and subjective definitions of the nationwide survey (Fox & Roehrig, 2015).

Codes for type of knowledge include factual, conceptual, and procedural knowledge (Krathwohl, 2002). Examples of assessment questions eliciting each type of knowledge are presented in Table 4.3.

Table 4.3

Examples for Type of Knowledge

Type of Knowledge	Example Question
Factual	State the first law of thermodynamics.
Conceptual	Explain what happens to ΔU and ΔH during a reversible adiabatic expansion of an ideal gas.
Procedural	Calculate q, w, ΔU and ΔH for a reversible isothermal expansion of 1.00 mol of Ar, from 12.0 L 26.0 L, at 273 K.

Codes for type of cognitive process include remember, understand, apply, analyze, evaluate, and create (Krathwohl, 2002). Examples of assessment questions eliciting each type of cognitive process are presented in Table 4.4.

Table 4.4

Examples for Type of Cognitive Process

Type of Cognitive Process	Example Question
Remember	True or False: The potential energy for a particle in a box is zero within the box.
Understand	Rank the following in order of increasing bond dissociation energy: O_2^-, O_2^+, O_2.
Apply	Calculate the reduced mass, moment of inertia, and rotational constant for an HF molecule with a bond length of 91.7 pm. The mass of H is $1.008*10^{-27}$ kg and the mass of F is $3.155*10^{-26}$ kg.
Analyze	Consider a molecule of methylamine, CH_3NH_2. What symmetry elements are present and what is the point group?
Evaluate	Show that the eigenvalues of a Hermitian operator are real.
Create	Draw the molecular orbital diagram for OF^-. Assign electrons to the molecular orbitals and label each atomic orbital, molecular orbital, the HOMO, and the LUMO.

Using the criteria above, the primary researcher coded two semesters of thermodynamics exams and two semesters of quantum mechanics exams, which represented 10% of the total sample. To determine intra–rater reliability, the primary researcher coded the same exams again after two weeks. An intra–rater reliability of 96% was obtained. To determine inter–rater reliability, a second researcher coded the same subset of exams as the primary researcher. An inter–rater reliability of 88% was obtained. Differences were resolved through discussion.

After all of the assessment questions were coded, a quantitative and qualitative analysis was conducted. For the quantitative analysis, a series of descriptive and inferential statistics were computed using the statistical package, R (R Core Team, 2014). First, mean frequencies of each assessment characteristic were computed. Next, Chi–Squared analyses were conducted to investigate how the distribution of assessment characteristics of instructors from different types of institutions compared to the overall distribution, as well as how the features of one assessment characteristic were distributed among features of another assessment characteristic.

While the quantitative analysis provides an overview of assessment characteristics, the qualitative analysis provides a rich description of the assessments of select instructors. Seven instructors, who represent different trends of assessment practices, were selected for the qualitative analysis. These seven instructors were given pseudonyms to protect their anonymity and confidentiality. Pseudonyms were assigned based on the most popular names in the U.S. over the last 100 years, where the first instructor presented was given the most popular name, the second instructor was given the second most popular name, and so on (Social Security Administration, 2015). Pseudonyms reflect the gender of the instructor.

4.4. Results

The results are divided into two sections. The first section presents an overview of assessment characteristics from a quantitative perspective. The second section presents the assessment practices of individual instructors from a qualitative perspective.

4.4.1. Physical Chemistry Assessments: A Quantitative Perspective

In total, 4336 assessment questions from 169 exams were analyzed. The questions were evenly divided between thermodynamics and quantum mechanics, with 2122 thermodynamics questions (49%) from 84 thermodynamics exams and 2214 quantum mechanics questions (51%) from 85 quantum mechanics exams. On average, each instructor gave four exams in a single semester, with the total number of exams per semester ranging from 2 to 8. Also, on average each exam contained 26 questions, although the number questions per exam varied widely from a minimum of 7 questions to a maximum of 87 questions.

4.4.1.1. Question Format: Objective and Subjective

The 169 physical chemistry assessments contained more subjective questions than objective questions (Table 4.5). Overall, 2990 questions were subjective in nature (69%) and 1346 questions were objective in nature (31%). Subjective questions included short answer and open–ended problems. There were 1744 short answer questions (40%) and 1246 open–ended problems (29%). Objective questions included multiple–choice, matching, and true or false questions. There were 924 multiple–choice questions (21%), 224 matching questions (5%) and 198 true or false questions (5%).

To investigate how the distribution of objective and subjective questions at different institutions compared to the overall distribution, a Chi–Squared analysis was conducted (Table 4.5). Instructors at baccalaureate and master's institutions gave significantly more subjective questions, while instructors at doctorate institutions gave significantly more objective questions. In fact, instructors at doctorate institutions, on average, used objective style questions more frequently than subjective style questions, a trend contrary to the average.

Table 4.5 *Chi–Squared Analysis of Question Format and Type of Institution*

Observed Frequency (%)	Question Format	
Institution	Objective	Subjective
All	31	69
Baccalaureate	26	74*
Master's	20	80*
Doctorate	57*	43

*Observed frequency greater than expected frequency, adjusted standardized residual > 3.0

In the nationwide survey, instructors reported using subjective style questions more frequently than objective style questions (Fox & Roehrig, 2015). While there is agreement for the dominant question format between what instructors reported and how instructors actually assessed, there is disagreement in the degree of to which subjective style questions outnumber objective style questions. In the nationwide survey, instructors reported that 87% of their assessment questions were subjective in nature, while the assessment analysis found that instructors actually use an average of 69% subjective style questions. While the instructors who elected to share their assessments may not be representative of the instructors who participated in the nationwide survey, instructors may also not be cognizant of the actual ratio of subjective and objective style questions present in their assessments.

4.4.1.2. Type of Knowledge: Factual, Conceptual, and Procedural

The type of knowledge elicited by physical chemistry assessment questions was approximately evenly distributed among factual, conceptual and procedural knowledge (Table 4.6). There were 1312 factual questions (30%), 1540 conceptual questions (36%), and 1484 procedural questions (34%).

To investigate how the distribution of factual, conceptual and procedural questions at different institutions compared to the overall distribution, a Chi–Squared analysis was conducted (Table 4.6). Instructors at baccalaureate institutions gave significantly more conceptual questions, instructors at master's institutions gave significantly more procedural questions, and instructors at doctorate institutions gave significantly more factual questions. While significant differences are evident, the change in frequencies are small, and consequently less meaningful.

Table 4.6

Chi–Squared Analysis of Type of Knowledge and Type of Institution

Observed Frequency (%)	Type of Knowledge		
Institution	Factual	Conceptual	Procedural
All	30	36	34
Baccalaureate	25	41*	34
Master's	30	33	37*
Doctorate	36*	34	30

*Observed frequency greater than expected frequency, adjusted standardized residual > 3.0

In the nationwide survey, instructors reported the frequency of mathematical assessment questions (Fox & Roehrig, 2015). While instructors reported that their assessments contained 62% mathematical questions, the assessment analysis found that only 34% of assessment questions required procedural knowledge. This discrepancy may be due to the shift from a mathematical definition to a procedural definition, or because instructors who elected to share their assessments may not be representative of the instructors who participated in the nationwide survey. Given that instructors reported using mathematical questions twice as often compared to the observed use of procedural questions, however, instructors may not be entirely cognizant of the role mathematics plays in their assessment practices.

The physical chemistry exams contained far more factual questions than the ACS general chemistry and organic chemistry exams. While the physical chemistry exams, on average, contained 30% factual items, the ACS general chemistry exam contained 10% factual items and the ACS organic chemistry exam contained only 1% factual items (Luxford et al., 2015; Raker & Holme, 2013). The differing frequency of factual questions may be due to the nature of the course; perhaps the abstract nature of physical chemistry may warrant more factual questions. The difference may also be due to the writers of the assessments; perhaps physical chemistry instructors place equal value among factual, conceptual and procedural questions, while the ACS Examinations Institute places a higher value on conceptual and procedural questions. Or perhaps the ACS Examinations Institute may be better equipped to write questions that elicit conceptual and procedural knowledge compared physical chemistry instructors.

4.4.1.3. Type of Cognitive Process: Bloom’s Taxonomy

There were more questions that elicited the simpler cognitive processes at the lower end of Bloom’s taxonomy compared to the more complex cognitive processes at the upper end of Bloom’s taxonomy (Table 4.7). On the bottom half of Bloom’s taxonomy, there were 1201 questions that required students to remember (28%), 1345 questions that required students to understand (31%), and 1189 questions that required students to apply (27%). In total, 86% of all assessment questions utilized the simpler cognitive processes located on the bottom half of Bloom’s taxonomy. At the top half of Bloom’s taxonomy, there were 231 questions that required students to analyze (5%), 152 questions that required students to evaluate (4%) and 218 questions that required students to create (5%). In total, only 14% of all assessment questions utilized the more complex cognitive processes located on the top half of Bloom’s taxonomy.

To investigate how the distribution of questions along Bloom’s taxonomy at different institutions compared to the overall distribution, a Chi–Squared analysis was conducted (Table 4.7). At the bottom of Bloom’s taxonomy, instructors at baccalaureate institutions gave significantly fewer questions that required students to remember, while instructors at doctorate institutions gave significantly more questions that required students to remember and fewer questions that requires students to apply. On the upper half of Bloom’s taxonomy, instructors at baccalaureate institutions gave significantly more questions that required students to evaluate, while instructors at doctorate institutions gave significantly more questions that required students to analyze, but also fewer questions that required students to evaluate or create. There were no significant differences for instructors at master’s institutions. While significant differences are evident, the change in frequencies are small, and consequently less meaningful.

Table 4.7

Chi–Squared Analysis for Type of Cognitive Process and Type of Institution

Observed Frequency (%)	Level of Cognitive Rigor					
Institution	Remember	Understand	Apply	Analyze	Evaluate	Create
All	28	31	27	5	4	5
Baccalaureate	24*	32	29	4	5**	6
Master’s	27	30	29	5	3	6
Doctorate	32**	33	23*	7**	2*	3*

*Observed frequency less than expected frequency, adjusted standardized residual < 3.0

**Observed frequency greater than expected frequency, adjusted standardized residual > 3.0

The type of cognitive process was not assessed in the nationwide survey or in prior ACS exams studies. Consequently, the type of cognitive process of instructor–written physical chemistry assessments cannot be compared to what instructors reported in the nationwide survey or with the analysis of ACS general and organic chemistry exams. This data, however, may serve as a foundation for future studies regarding the type of cognitive processes of both instructor–written assessments and ACS exams.

4.4.1.4. Type of Cognitive Process vs. Type of Knowledge

To investigate how questions at each level of Bloom’s taxonomy were distributed among questions that elicited factual, conceptual, or procedural knowledge, a Chi–Squared analysis was conducted (Table 4.8). Nearly every question that required students to remember elicited factual knowledge. The majority of questions that required students to understand and create elicited conceptual knowledge. The majority of questions that required students to apply, analyze or evaluate elicited procedural knowledge. Thus, factual knowledge was associated with the least complex cognitive process, while conceptual and procedural knowledge were associated with a broad range of cognitive processes. Examples of questions that use specific pairings of cognitive processes and type of knowledge are presented later, when the assessment practices of selected instructors are examined.

Table 4.8

Chi–Squared Analysis of Type of Cognitive Process and Type of Knowledge

Observed Frequency (%)	Type of Knowledge		
Type of Cognitive Process	Factual	Conceptual	Procedural
Remember	99*	1	0
Understand	8	82*	10
Apply	0	6	94*
Analyze	0	83*	17
Evaluate	0	0	100*
Create	0	82*	18

*Observed frequency greater than expected frequency, adjusted standardized residual > 3.0

4.4.1.5. Type of Cognitive Process vs. Question Format

To investigate how questions at each level of Bloom's taxonomy were distributed between objective and subjective questions, a Chi–Squared analysis was conducted (Table 4.9). The majority of questions that required students to remember had an objective format. In contrast, the majority of questions that required students to apply, evaluate, or create had a subjective format. Consequently, the simplest cognitive process was predominantly assessed via an objective format, while the most complex cognitive processes were predominantly assessed via a subjective format. Examples of questions that assess different cognitive processes via objective and subjective formats are presented later, when the assessment practices of selected instructors are examined.

Table 4.9

Chi–Squared Analysis of Type of Cognitive Process and Question Format

Observed Frequency (%)	Question Format	
Type of Cognitive Process	Objective	Subjective
Remember	59*	41
Understand	29	71
Apply	15	85*
Analyze	24	76
Evaluate	2	98*
Create	0	100*

*Observed frequency greater than expected frequency, adjusted standardized residual > 3.0

4.4.1.6. Type of Knowledge vs. Question Format

To investigate how questions that elicited factual, conceptual, or procedural knowledge were distributed between objective and subjective questions, a Chi–Squared analysis was conducted (Table 4.10). The majority of questions that elicited factual knowledge had an objective format. In contrast, the majority of questions that elicited procedural knowledge had a subjective format. There was no significant difference for the format of conceptual questions. Thus, while conceptual questions were fittingly distributed between objective and subjective questions, questions that required factual knowledge were predominantly assessed via an object format and questions that required procedural knowledge were predominantly assessed via a subjective format. Examples of questions that assess different types of knowledge via objective and subjective formats are presented later, when the assessment practices of selected instructors are examined.

Table 4.10

Chi–Squared Analysis of Type of Knowledge and Question Format

Observed Frequency (%)	Question Format	
Type of Knowledge	Objective	Subjective
Factual	58*	42
Conceptual	29	71
Procedural	10	90*

*Observed frequency greater than expected frequency, adjusted standardized residual > 3.0

4.4.1.7. American Chemical Society Physical Chemistry Exams

While the main focus of this study was to investigate characteristics of assessments written by instructors, it is important to make note of instructors' use of ACS physical chemistry exams. Twelve of the 27 participating instructors elected to use ACS exams as a component of their final exam. Ten instructors gave both the thermodynamics and quantum mechanics physical chemistry ACS exams. One instructor only used the thermodynamics physical chemistry ACS exam because this instructor only taught thermodynamics, not quantum mechanics. One instructor only used the quantum mechanics physical chemistry ACS exam, although this instructor taught both thermodynamics and quantum mechanics. The remaining 15 instructors chose to not use any ACS physical chemistry exam. While the majority of instructors elected not to use ACS physical chemistry exams, a large portion of instructors did elect to use ACS physical chemistry exams, which suggests that the implications of using or not using ACS exams requires further investigation.

Of the twelve instructors who opted to use the ACS physical chemistry exam, all twelve instructors reported that they use ACS exams as a means to compare their students with students across the country. Nine of the twelve instructors reported that they also use

ACS exams in order to compare current students to past students. Only one of the twelve instructors reported that they use ACS exams to compare students in their physical chemistry course with students enrolled in physical chemistry with a different instructor at his or her institution. An investigation of why instructors elect to use ACS physical chemistry exams may, in part, help explain the advantages and disadvantages of using ACS exams.

4.4.2. Physical Chemistry Assessments: A Qualitative Perspective

Seven instructors were selected for further analysis because they represent extremes, trends, or anomalies of assessment characteristics. James and John were selected because they utilized more complex and simpler cognitive processes, respectively. Robert, Michael, and William were selected because they had a high frequency of questions that elicited factual, conceptual, and procedural knowledge, respectively. David and Richard were selected to show that neither subjective nor objective questions are inherently better or worse than the other.

4.4.2.1. James: Complex Cognitive Processes

James has been teaching physical chemistry for 1–5 years at a medium–sized, public university in the Northeast that grants up to master's degrees in chemistry. James was selected for further analysis for two reasons. First, James represents an extreme due to his frequent use of more complex cognitive processes. Second, James exemplifies a trend due to the association between his use of complex cognitive processes with fewer questions that elicited factual knowledge and more questions with a subjective format (Table 4.11).

Table 4.11
James' Assessment Characteristics

	Format (%)		Type of Knowledge (%)			Type of Cognitive Process (%)*					
Instructor	Objective	Subjective	Factual	Conceptual	Procedural	1	2	3	4	5	6
All	31	69	30	36	34	28	31	27	5	4	5
James	0	100	0	55	45	0	45	19	3	16	17

*1 = Remember, 2 = Understand, 3 = Apply, 4 = Analyze, 5 = Evaluate, 6 = Create

James used the complex cognitive process of evaluate at a frequency four times greater than the average. Thus, James serves as an extreme for his high frequency of evaluating questions. James also exemplifies the association between the cognitive process of evaluate and procedural knowledge because his questions that required students to evaluate primarily elicited procedural knowledge. For example, one question stated: "Explicitly show whether or not the $n = 3$ wavefunction for a particle in a one–dimensional box is an eigenfucntion of the momentum operator." A similar question required students to complete another proof using the Hamiltonian operator. Another example: "Given the wavefunction above, show that it is not an energy eigenfucntion." A sequential question then required students to show that the wavefunction is normalized. These examples show how questions that required evaluating and procedural knowledge were typically proofs or derivations.

James also used the cognitive process of create at a frequency three times greater than the average. Thus, James serves as an extreme for his high frequency of creating questions. James also exemplifies the association between the cognitive process of create and conceptual knowledge because his questions that required students to create primarily elicited conceptual knowledge. For example, one question stated: “Sketch the orbital, radial wavefunction, and radial probability function for $3p_y$ orbital.” Sequential questions required students to make similar sketches and graphs for the 2s and $3d_{xz}$ orbitals. Another example: “Sketch the molecular orbital diagram for the ground state of N_2.” For this question, students were required to label and draw both the atomic and molecular orbitals. These examples show how questions that required creating and conceptual knowledge typically involved drawing a picture, making a graph, or constructing a molecular orbital diagram.

While James used the more complex cognitive processes of evaluate and create at a higher frequency compared to the average, he also used the simplest cognitive process at a much lower frequency than the average. In fact, James’ assessments did not contain any questions that required students to remember. James also did not have any assessment questions that elicited factual knowledge. Thus, James represents an extreme for not using remembering or factual knowledge, and also exemplifies the association between remembering and factual knowledge since none of his questions used either assessment characteristic.

All of James’ assessment questions had a subjective format. Recall that increased use of subjective questions was associated with decreased use of factual knowledge and the cognitive process of remember, as well as increased use of the cognitive processes of evaluate and create. Thus, James serves as an extreme for only using subjective formatting, and also exemplifies the association between subjective formatting with less factual knowledge and more complex cognitive processes.

In conclusion, James represents an instructor who utilizes more complex cognitive processes, no factual knowledge, and only subjective formatting. It is interesting to note that James is a novice instructor, with only 1–5 years of teaching experience, yet he is able to design assessments that do not encourage students to remember facts, but rather help students extend their understanding with more challenging or stimulating questions.

4.4.2.2. John: Simple Cognitive Processes

John has been teaching for over 20 years at a large, public university in the Midwest that grants doctorate degrees in chemistry. John was selected for further analysis for two reasons. First, John represents an extreme due to his frequent use of simpler cognitive processes. Second, John exemplifies a trend due to the association between his use of simple cognitive processes with more questions that elicited factual knowledge and more questions with an objective format (Table 4.12).

Table 4.12

John's Assessment Characteristics

	Format (%)		Type of Knowledge (%)			Type of Cognitive Process (%)*					
Instructor	Objective	Subjective	Factual	Conceptual	Procedural	1	2	3	4	5	6
All	31	69	30	36	34	28	31	27	5	4	5
John	100	0	47	39	14	46	39	15	0	0	0

*1 = Remember, 2 = Understand, 3 = Apply, 4 = Analyze, 5 = Evaluate, 6 = Create

John used the simplest cognitive process of remember at a frequency almost two times greater than the average, and his questions that required students to remember primarily elicited factual knowledge. For example, one question stated: "Which of the following are state functions? (a) Internal energy, (b) Gibbs free energy, (c) Entropy, (d)

Work, (e) Internal energy, Gibbs free energy, and Entropy, (f) All of the above." This question required students to recall the definition of a state function, as well as the definition of each term listed as an answer choice, but did not compel students to extend their understanding. Another example: "What is b roughly equal to for a real gas? (a) The Lennard–Jones σ value, (b) 1.0, (c) k_B, (d) h^2, (e) The volume of an individual gas molecule, (f) Avogadro's number." This question required students to recall the definition of the symbol, b, and again did not compel students to extend their understanding. Thus, John represents an extreme for his high frequency of remembering questions. John also exemplifies the association between remembering and factual knowledge because his questions that required students to remember primarily elicited factual knowledge.

While John's remembering questions primarily elicited factual knowledge, his understanding and application questions primarily elicited conceptual and procedural knowledge, respectively. In fact, the frequency of factual, conceptual, and procedural questions is nearly equivalent to the frequency of questions that required remembering, understanding, and applying, respectively. An example of a conceptual understanding questions was: "Which of the following molecules, under classical conditions, has the largest constant–volume heat capacity? (a) He, (b) H_2O, (c) $CHCl_3$, (d) CO_2, (e) Xe, (f) UF_2." This question required students to recall the definition of constant–volume heat capacity, and then extend their understanding by comparing the properties of the given molecules. An example of a procedural application questions was: "A substance has a molar constant volume heat capacity of 10 J/mol*K. How much energy is required to raise the temperature of two moles of the substance from 150 to 300 K at constant volume and assuming no phase transition occurs over this temperature range? (a) 1.5 kJ, (b) 6 K/mol, (c) 5 kJ, (d) 1.5 J, (e) 15 J/mol, (f) 3 kJ." This question required students to understand how to apply the given information to calculate the requested quantity.

While John used the simplest cognitive process of remembering at a higher frequency compared to the average, he also used the more complex cognitive processes at a much lower frequency than the average. In fact, John's assessments did not contain any questions that required students to analyze, evaluate, or create. It is interesting to note that while about half of John's questions utilized factual knowledge and the cognitive process of remembering, and the other half of his questions were either conceptual understanding questions or procedural applying questions, each question was worth the same number of points. Thus, John did not value one type of question, and consequently one type of knowledge or cognitive process, over another.

All of John's assessment questions had an objective format. Recall that increased use of objective questions was associated with increased use of factual knowledge and the cognitive process of remembering, as well as decreased use of the cognitive processes of evaluate and create. Thus, John represents an extreme for only using objective formatting, and also exemplifies the association between objective formatting with more factual knowledge and simpler cognitive processes.

In conclusion, John represents an instructor who utilizes simpler cognitive processes, increased factual knowledge, and increased objective formatting. It is interesting to note that John is an experienced instructor, with more than 20 years of teaching experience, yet his assessments did not help students extend their understanding with challenging or stimulating questions, but instead used questions that primarily required students to remember facts.

4.4.2.3. Robert: High Factual Frequency

Robert has been teaching for 1–5 years at a large, public university in the South that grants doctorate degrees in chemistry. Robert was selected for further analysis for two reasons. First, Robert represents an extreme due to his frequent use of factual knowledge. Second, Robert exemplifies a trend due to the association between his use of factual knowledge with the simple cognitive process of remember and an objective format (Table 4.13).

Table 4.13

Robert's Assessment Characteristics

	Format (%)		Type of Knowledge (%)			Type of Cognitive Process (%)*					
Instructor	Objective	Subjective	Factual	Conceptual	Procedural	1	2	3	4	5	6
All	31	69	30	36	34	28	31	27	5	4	5
Robert	60	40	60	28	12	60	22	8	8	1	1

*1 = Remember, 2 = Understand, 3 = Apply, 4 = Analyze, 5 = Evaluate, 6 = Create

Robert's assessment questions utilized factual knowledge twice as often compared to the average. His assessment questions also used the cognitive process of remembering, as well as an objective format, twice as often compared to the average. In fact, over half of Robert's questions incorporated all three of those assessment characteristics.

All of Robert's exams contained 15 matching questions. These questions were objective in nature, since students selected the correct answer from a set of possible answers, and required both factual knowledge and the cognitive process of remember.

The matching questions asked students to pair together opposite sides of formulas. For example, one question required students to match $H\Psi$ with $E\Psi$, testing students' ability to recall the Schrödinger equation. Another example asked students to match $\Delta x \Delta p$ with $h/4\pi$, testing students' ability to recall the Heisenberg uncertainty principle. These matching questions required students to recall facts, and did not compel students to extend their understanding.

While the majority of Robert's questions were objective questions that required factual knowledge and the cognitive process of remember, these questions did not represent the majority of points. Each exam had approximately five additional questions that utilized either conceptual or procedural knowledge, as well as more complex cognitive processes of understanding, applying, and analyzing. These questions represented about 85% of the possible points, while the matching questions represented about 15% of the possible points. Thus, while the majority of Robert's assessment questions had an objective format that required students to remember facts, the majority of the points were associated with subjective questions that elicited conceptual or procedural knowledge and utilized more complex cognitive processes.

In the previous section, it was observed that about half of John's questions combined the cognitive process of remember with factual knowledge and an objective format. About half of John's questions, and more than half of Robert's questions, incorporated all three of those assessment characteristics. While Robert had a greater frequency of these questions, they represented a larger proportion of points on John's assessments. In fact, John's use of such questions represented half of the point value of his assessments, yet Robert's increased use of such questions only represented about 15%

of the point value of his assessments. Thus, while Robert combined factual knowledge, the cognitive process of remembering, and an objective format at a higher frequency compared to John, Robert placed a much lower value on those questions compared to John.

In conclusion, Robert represents an instructor who combined factual knowledge, the cognitive process of remember, and an objective format. While the majority of his questions utilized these three assessment characteristics, the majority of his points were distributed among more challenging or stimulating questions. As an instructor at a doctorate institution, Robert may not have the time or resources to grade a large number of subjective style questions. These constraints may be the motivation for his high frequency, but low point value, of objective questions and low frequency, but high point value, of subjective questions. As a novice instructor, Robert seems to have found an efficient means of testing a range of different types of knowledge and cognitive processes.

4.4.2.4. Michael: High Conceptual Frequency

Michael has been teaching for 1–5 years at a small, private university in the Northeast that grants up to bachelor's degrees in chemistry. Michael was selected for further analysis for two reasons. First, Michael represents an extreme due to his frequent use of conceptual knowledge. Second, Michael exemplifies a trend due to the association between his use of conceptual knowledge with the cognitive process of understanding and a subjective format (Table 4.14).

Table 4.14
Michael's Assessment Characteristics

	Format (%)		Type of Knowledge (%)			Type of Cognitive Process (%)*					
Instructor	Objective	Subjective	Factual	Conceptual	Procedural	1	2	3	4	5	6
All	31	69	30	36	34	28	31	27	5	4	5
Michael	17	83	16	61	23	15	52	14	11	1	7

*1 = Remember, 2 = Understand, 3 = Apply, 4 = Analyze, 5 = Evaluate, 6 = Create

Michael's assessment questions utilized conceptual knowledge about twice as often compared to the average use of conceptual knowledge. His assessment questions also used the cognitive process of understanding, as well as a subjective format, more often compared to the average. In fact, half of Michael's questions incorporated all three of those assessment characteristics.

The majority of Michaels's questions were subjective, conceptual, understanding questions. For example, one question stated: "Select an experiment and then explain how classical mechanics failed and how quantization provided a better description of the observed phenomena." Michael's procedural questions were typically paired with a conceptual question that asked students to explain their answer, defend why their answer does or does not match a literature value, or discuss the validity of their answer based on their chemical intuition. These examples show how Michael used a subjective format to elicit conceptual knowledge and to assess students' ability to understand, explain, or compare.

In conclusion, Michael represents an instructor who combined conceptual knowledge, the cognitive process of understand, and a subjective format. As an instructor at a baccalaureate institution, Michael's class size is likely small enough to have sufficient time to to grade a large number of subjective style questions. It is interesting to note that Michael is a novice instructor, and seems to place higher value on conceptual knowledge compared to factual or procedural knowledge.

4.4.2.5. William: High Procedural Frequency

William has been teaching for 11–15 years at a medium–sized, public university in the West that grants up to master's degrees in chemistry. William was selected for further analysis for two reasons. First, William represents an extreme due to his frequent use of procedural knowledge. Second, William exemplifies a trend due to the association between his use of procedural knowledge with the cognitive process of apply and a subjective format (Table 4.15).

Table 4.15

William's Assessment Characteristics

	Format (%)		Type of Knowledge (%)			Type of Cognitive Process (%)*					
Instructor	Objective	Subjective	Factual	Conceptual	Procedural	1	2	3	4	5	6
All	31	69	30	36	34	28	31	27	5	4	5
William	0	100	6	12	82	6	12	82	0	0	0

*1 = Remember, 2 = Understand, 3 = Apply, 4 = Analyze, 5 = Evaluate, 6 = Create

William's assessment questions utilized procedural knowledge more than two times as often compared to the average use of procedural knowledge. His assessment questions also used the cognitive process of apply three times as often compared to the average, as well as more subjective questions compared to the average. In fact, over half of William's questions incorporated all three of those assessment characteristics.

The majority of William's questions were subjective, procedural applying questions. For example, one question stated: "One mole of a monoatomic ideal gas is compressed adiabatically and reversibly from 101 kPa to 1.01 MPa. The initial temperature is 300 K. Calculate: w, q, ΔU, ΔH, ΔS." Another question gave students a formula for the second order rate constant of a decomposition reaction and asked students to calculate the activation energy, the frequency factor, and the half–life given a temperature and initial reactant concentration. These examples show how William used a subjective format to assess students' ability to apply procedural knowledge.

In conclusion, William represents an instructor who combined procedural knowledge, the cognitive process of apply, and a subjective format. As an instructor at a master's institution, William's class size may be small enough to have adequate time to to grade a large number of subjective style questions. It is interesting to note that William is an experienced instructor, and seems to place higher value on procedural knowledge compared to factual or conceptual knowledge.

4.4.2.6. David: Weak Subjective Questions

David has been teaching for 6–10 years at a medium–sized, public university in the South that grants up to master's degrees in chemistry. David was selected for further analysis because he represents an anomaly; his predominant use of subjective questions was not associated with a decreased use of questions that elicited factual knowledge or a decreased used of questions that used the cognitive process of remembering (Table 4.16). In other words, David demonstrates how subjective questions do not necessarily correspond to more challenging or stimulating questions.

Table 4.16

David's Assessment Characteristics

	Format (%)		Type of Knowledge (%)			Type of Cognitive Process (%)*					
Instructor	Objective	Subjective	Factual	Conceptual	Procedural	1	2	3	4	5	6
All	31	69	30	36	34	28	31	27	5	4	5
David	14	86	59	15	26	56	17	23	1	2	1

*1 = Remember, 2 = Understand, 3 = Apply, 4 = Analyze, 5 = Evaluate, 6 = Create

David's assessment questions utilized a subjective format more often compared to the average. His assessment questions also used the cognitive process of remember, as well as factual knowledge, about twice as often compared to the average. Thus, David's assessment practices contradicted the positive association between a subjective format with the use of conceptual or procedural knowledge and more complex cognitive process.

For example, a set of questions asked students to state the first, second, and third laws of thermodynamics. Such questions required students to recall the definition of each law of thermodynamics, but students were not required to extend their understanding of each law. Another set of questions asked students to identify state functions and path functions. Such questions required students to recall the definitions of state and path functions, and then recognize examples of each definition. Thus, David's subjective questions required students to recall facts, and did not encourage students to extend their understanding.

In conclusion, David represents an instructor who used a subjective format combined with factual knowledge, as well as the simplest cognitive process of remembering. David's assessment practices show how a subjective format does not inherently warrant a more challenging or stimulating problem, nor does it automatically encourage students to extend their understanding.

4.4.2.7. Richard: Strong Objective Questions

Richard has been teaching for 11–15 years at a large, public university in the South that grants doctorate degrees in chemistry. Richard was selected for further analysis because he represents an anomaly; his predominant use of objective questions was not associated with an increased use of questions that elicited factual knowledge or an increased used of questions that used the cognitive process of remember (Table 4.17). In other words, Richard demonstrates how to write more challenging or stimulating questions in an objective format.

Table 4.17
David's Assessment Characteristics

	Format (%)		Type of Knowledge (%)			Type of Cognitive Process (%)*					
Instructor	Objective	Subjective	Factual	Conceptual	Procedural	1	2	3	4	5	6
All	31	69	30	36	34	28	31	27	5	4	5
Richard	90	10	17	71	12	14	53	8	20	1	4

*1 = Remember, 2 = Understand, 3 = Apply, 4 = Analyze, 5 = Evaluate, 6 = Create

Richard's assessment questions utilized an objective format three times as often compared to the average. His assessment questions also used the cognitive processes of understand and analyze, as well as conceptual knowledge, about twice as often compared to the average. Thus, Richard's assessment practices contradicted the positive association between an objective format with the use of factual knowledge and the cognitive process of remember.

For example, Richard presented students with a set of molecular structures and asked students to analyze the molecule to determine its point group. Students were given four possible point groups to choose from, as well as a choice for none of the above. Another example, students were asked why particular elements had a high or low first ionization energy. Students were given four rich descriptions to choose from, as well as a choice for none of the above. Thus, Richard's objective questions did not require students to recall facts, and instead encouraged students to extend their understanding, analyze information, and explain why chemical phenomena occur.

In conclusion, Richard represents an instructor who used an objective format combined with conceptual and procedural knowledge, as well as more complex cognitive processes. Richard's assessment practices show how an objective format does not inherently warrant a less challenging or stimulating problem, or prohibit students from extending their understanding. As an instructor at a doctorate institution, Richard likely has a large class size that constrains him to an objective format. Despite this constraint, it appears that Richard places a high value on conceptual questions that involve understanding and analyzing, and less value on factual and procedural knowledge. Richard's lack of questions that require students to remember facts may be due to his experience as an instructor. Also, since objective questions typically do not allow for partial credit, Richard may use fewer procedural questions to eliminate the need or desire to give partial credit for multi–step problems.

4.5. Discussion

Given the large number of questions analyzed (*N* = 4336), and that the participating instructors are from institutions of different types, demographics, and research activity, the results of the assessment analysis represent a variety of physical chemistry courses across the country. This study is not without its limitations, however. Given the voluntary sampling, the participants who elected to share their assessments may not be representative of physical chemistry instructors across the country. Consequently, the assessment characteristics of the participants who volunteered for the study may not be representative of instructor–written physical chemistry assessments across the country. Also, the quantitative analysis did not include class size or the weighting of questions. While the implications of class size can be inferred based on the type of institution, the weighting of items is a larger limitation because not all questions may be worth the same number of points. Consequently, the number of questions with various assessment characteristics may not correspond to the number of points associated with various assessment characteristics. Despite these limitations, the results of this survey show four important themes physical chemistry assessment practices. First, subjective formatting was more common than objective formatting. Second, there was an approximate even distribution among questions that elicited factual, conceptual, and procedural knowledge. Third, simpler cognitive processes were more common than more complex cognitive processes. Fourth, question format does not necessarily dictate the type of knowledge or type of cognitive process.

First, on average there were twice as many subjective style questions compared to objective style questions. This ratio was more extreme for baccalaureate and master's institutions and reversed for doctorate institutions. This trend among different types of institutions is likely due to class size. Class sizes are typically smaller at baccalaureate and master's institutions, and instructors likely have adequate time to grade the high frequency of subjective questions. In contrast, class sizes are typically larger at doctorate institutions, and grading a high frequency of subjective questions for a large number of students likely becomes impractical for instructors.

Second, there was an approximately even distribution among questions that elicited factual, conceptual, and procedural knowledge. This distribution of type of knowledge conflicts with the distribution of type of knowledge evident in ACS general and organic chemistry exams. The frequency of procedural questions evident in instructor–written physical chemistry exams is similar to the frequency found in the ACS general chemistry exams, and greater than the frequency found in ACS organic chemistry exams (Luxford et al., 2015; Raker & Holme, 2013). This trend is not surprising given the stronger mathematical presence in general and physical chemistry compared to organic chemistry. What is more surprising however, is that instructor–written physical chemistry exams utilized factual knowledge at a much higher frequency compared to the ACS general or organic chemistry exams. While a third of physical chemistry questions elicited factual knowledge, only 10% of general chemistry and 1% of organic chemistry questions elicited factual knowledge (Luxford et al., 2015; Raker & Holme, 2013). The much higher frequency of factual questions in instructor–written physical chemistry exams may be due to the challenging and abstract nature of physical chemistry. Since conceptual and procedural questions typically use more complex cognitive processes, the simpler cognitive processes of factual questions may be appropriate given the difficult nature of physical chemistry. Or perhaps physical chemistry instructors are unaware of how to use different knowledge types, or do not see value in eliciting conceptual and procedural knowledge more frequently than factual knowledge.

Third, the majority of questions utilized a cognitive process from the bottom half of Bloom's taxonomy, with approximately equal representation of questions that required students to remember, understand, and apply. Only 14% of questions used cognitive processes from the top half of Bloom's taxonomy, with approximately equal representation of questions that required students to analyze, evaluate, and create. The majority of questions that required students to remember elicited factual knowledge, the majority of questions that required students to understand, analyze or create elicited conceptual knowledge, and the majority of questions that required students to apply or evaluate elicited procedural knowledge. Thus, factual questions were associated with the simplest cognitive process while conceptual and procedural questions were associated with a range of cognitive processes.

Fourth, the association between different types of knowledge and cognitive processes was stronger than the association between format and type of knowledge or cognitive process. In other words, the format of a question does not necessarily dictate the type of knowledge or cognitive process. Both objective and subjective questions can elicit factual, conceptual or procedural knowledge, as well as a range of cognitive processes. As discussed earlier, class sizes may dictate the selected question format, but class size does not have to dictate the challenging or stimulating nature of assessment questions.

In conclusion, characteristics of instructor–written physical chemistry exams were analyzed through a broad, quantitative lens and through a narrower, qualitative lens. Next, implications of these themes are presented.

4.6. Implications for Teaching

Instructor–written physical chemistry assessments contained questions that elicited different types of knowledge, utilized different cognitive processes, and were formatted in different ways. Given the variation of questions, both within the assessment materials of individual instructors and across the assessment materials of multiple instructors, it is challenging to conclude specific directions that instructors should follow when writing exams. Instead of proposing what instructors should include in their assessments, a process of designing assessments will be presented.

Before writing any assessment materials, instructors should identify the learning goals of their course. Learning goals may consist of facts students should remember, concepts students should understand, or skills students should be able to apply. Only after instructors have clear, explicit learning goals should assessment materials be developed. With the learning goals at the forefront, assessment materials should be designed to measure students' mastery of the learning goals. When writing assessments, instructors should consider three key factors: the value of different types of knowledge, the value of different cognitive processes, and the value of question formatting.

First, instructors should consider the value of designing questions that assess students' factual, conceptual, or procedural knowledge. The valuation should align with the previously stated learning goals. For example, consider the following learning goal: students should be able to identify isothermal, isobaric, isochoric, and adiabatic processes. An appropriate question may ask students to identify the variable that remains constant in each of those processes, which would elicit students' factual knowledge. Consider another learning goal: students should be able to explain the direction of energy flow during isothermal, isobaric, isochoric, and adiabatic processes. An appropriate question may ask students to explain why heat is either leaving or entering the system, or why either the system or surroundings is doing work, during a particular process. This question elicits students’ conceptual knowledge. Consider a final learning goal: students should be able to calculate the amount of energy entering or leaving a system during isothermal, isobaric, isochoric, and adiabatic processes. An appropriate question may ask students to calculate the work of an isothermal expansion of one mole of argon gas. This question elicits students’ procedural knowledge. In addition to matching learning goals with the appropriate type of knowledge, instructors should consider how and when to assess different pairings of learning goals and type of knowledge. For example, it may be beneficial to assess the first learning goal that elicited factual knowledge via a formative assessment in the middle of a particular unit. This would allow instructors to monitor student understanding. Then, the second and third learning goals that elicited conceptual and procedural knowledge could be assessed via a summative assessment at the end of a particular unit. This would allow students to extend their understanding. Such differentiation among learning goals, type of knowledge, and type of assessment would require instructors to comprehend the differences between formative and summative assessment (Emenike, Raker & Holme, 2013; Raker, Emenike & Holme, 2013).

Second, instructors should consider the value of designing questions that assess various complexities of cognitive processes, and the valuation should align with the previously stated learning goals. In the three learning goals stated above, each learning goal would require students to remember, understand, and apply, respectively. These three cognitive processes, which represent the bottom half of Bloom’s taxonomy, are the cognitive processes most frequently used by instructors. Instructors, however, should strive to use the entire range of cognitive processes so that students are encouraged to extend their understanding. Instructors must be careful, however, to not teach only using the simplest cognitive processes and then asses more complex cognitive processes, because students may struggle ascending Bloom's taxonomy (Pungente & Badger, 2003; Crowe, Dirks & Wenderoth, 2008). Instead, instructors should incorporate a range of cognitive processes into both their teaching strategies and assessment materials to support students' development.

Third, instructors should consider the ability of different question formats to assess the target knowledge and cognitive processes, as well as the feasibility of grading different question formats. Although there was an association between objective questions that elicited factual knowledge and used simpler cognitive processes, select instructors demonstrated how this association can be transformed. Both objective and subjective style questions can elicit factual, conceptual, or procedural knowledge, and use a range of cognitive processes. For example, instead of creating a molecular orbital diagram via a subjective question, students could select the correct diagram or analyze a given diagram via an objective question. Another example, instead of deriving a formula via a subjective question, students could select the appropriate interpretation of the formula or eliminate an incorrect step of the derivation via an objective question. The ability to utilize different types of knowledge and cognitive processes in both objective and subjective style questions gives greater flexibility to instructors. If the time necessary to grade subjective questions of a large class is unrealistic, instructors can instead utilize objective questions without losing the variety of knowledge types or more complex cognitive processes.

Finally, after instructors have determined the learning goals of their course, and developed assessments that measure students' mastery of the learning goals, instructors should consider how their instructional strategies will facilitate students' mastery of the learning goals. Thus, instructional strategies serve as the bridge between learning goals and assessment. The bridge cannot be built until the learning goals and assessment materials are established, the bridge will lead to the wrong place if assessment materials do not appropriately measure mastery of learning goals, and the bridge will collapse if instructional strategies do not effectively support the mastery of learning goals. Ultimately, advice for instructors as they develop a course is as follows: first, state the learning goals, second, design assessment materials, and finally, plan instructional strategies.

5. Instructor Reflections on Teaching and Learning Physical Chemistry

5.1. Rationale

The nationwide survey of physical chemistry described in Chapter 3 found that there was a continued need to investigate the pedagogical content knowledge (PCK) of instructors. This need was primarily motivated due to minimal teacher preparation experience, as well as the lack of association between increased teacher preparation experience with transformed teaching practices. Ultimately, the nationwide survey provided an outlet for instructors to share their voice regarding the teaching and learning of physical chemistry. Instructor perceptions are imperative in higher education because, while K–12 education has national and state standards that dictate much of the concepts and skills that are taught in classrooms (Next Generation Science Standards, 2013), such explicit and encompassing standards do not exist for higher education. This gives instructors a greater degree of autonomy and choice in the development and facilitation of their curriculum. If impactful changes are to be made for the teaching and learning of physical chemistry, the critical role of the instructor, including their perceptions and PCK, should be central to such research.

The purpose of this study was to utilize instructor reflections on the teaching and learning of physical chemistry to provide a rich description of the PCK of physical chemistry instructors. The reflection questions asked instructors to describe successful and challenging teaching moments, as well as what they strive to change about their teaching, all while eliciting instructors' orientation towards teaching, knowledge of curriculum, knowledge of students’ understanding, and knowledge of instructional strategies.

This study expands prior research regarding the challenges of teaching and learning physical chemistry. One challenge of physical chemistry education was the limited PCK of instructors. Recall that instructors, who are primarily trained as researchers and not educators, often have strong content knowledge but weaker pedagogical knowledge, and consequently weaker PCK (Padilla & Van Driel, 2011). This study used reflections to investigate instructors’ PCK, and expands prior research by associating components of PCK with descriptions of successful teaching moments, challenging teaching moments, and proposed changes. Another challenge of physical chemistry education was the role of mathematics. Recall that prior research investigated the relationship between students’ prerequisite mathematical ability and success in physical chemistry (Hahn & Polik, 2004; Nicoll & Francisco, 2001; Derrick & Derrick, 2002). This study further investigated the unclear role of mathematics by identifying how instructors depict mathematics in their reflections. A final challenge of physical chemistry education was the negative perceptions exhibited by both instructors and students. Recall that both students and instructors had negative perceptions of physical chemistry, but the root of those perceptions varied between students and instructors (Sözbilir, 2004). This study further investigated perceptions of instructors by analyzing how instructors depict successes and challenges in their reflections, and then associating those perceptions with their PCK.

Ultimately, the purpose of this study was to address the following research question: What do instructor reflections on the teaching and learning of physical chemistry reveal about the PCK of physical chemistry instructors?

5.2. Literature Review

5.2.1. Development of the Pedagogical Content Knowledge Model

In 1987 Shulman developed the concept of PCK, which he described as the ability for educators to use their pedagogical knowledge to facilitate the development of content knowledge for students. Before Shulman, the prevailing theory was that teachers' knowledge were comprised solely of their understanding of content knowledge and pedagogical knowledge. Shulman introduced PCK as a third type of knowledge, unique to teachers, based on their ability to adapt and convey concepts for students. According to Shulman (1987), "pedagogical knowledge…goes beyond knowledge of subject matter per se to the dimension of subject matter knowledge for teaching" (p. 8). In this way Schulman's definition of PCK blends the traditional understandings of content knowledge and pedagogical knowledge into a unique concept of how teachers organize and represent knowledge for diverse learners (1987).

Shulman's model for PCK was designed for teachers of all subject areas. In 1999, Magnusson, Krajcik, and Borko adapted Schulman's model to make specific for science instruction. This customized model for PCK has five components: orientation towards science teaching, knowledge of science curriculum, knowledge of students' understanding of science, knowledge of instructional strategies in science, and knowledge of assessment in science (Magnusson, Krajcik & Borko, 1999).

Each component of this adapted model of PCK can be applied to the undergraduate chemistry classroom. The first component is orientation towards science teaching, which involves instructors' knowledge and beliefs about the purposes and goals of their teaching (Magnusson, Krajcik & Borko, 1999). In physical chemistry this may include the decisions behind implementing a particular curricular element, pedagogical strategy, or assessment material, the latter which was discussed in Chapter 4. This first component focuses on the motivation behind decisions, not the decisions themselves. Given the nature of this component, it impacts the remaining four components of Magnusson's model of PCK.

The second component of Magnusson's model of PCK is knowledge of science curriculum, which involves the instructor's ability to articulate and facilitate learning goals (Magnusson, Krajcik & Borko, 1999). In physical chemistry this may include identifying the concepts and skills students should master, setting a pace so that necessary topics are appropriately covered, and arranging topics so that connections between topics can be developed. It also includes the selection of curricular materials, such as textbooks or technology, to support students in their mastery of the learning goals.

The third component of Magnusson's model of PCK is knowledge of students' understanding of science, which involves instructors' understanding of required prerequisite knowledge and skills, as well as potential areas of difficulty or misconceptions (Magnusson, Krajcik & Borko, 1999). In physical chemistry this may include a math review at the beginning of the course to bring students up to speed with the calculus or linear algebra needed for success in physical chemistry. It may also include disrupting the misconception that physical chemistry is a challenging, and potentially insurmountable course. Finally, it requires instructors to be cognizant of the diverse backgrounds and learning styles of their students.

The fourth component of Magnusson's model of PCK is knowledge of instructional strategies in science, which involves instructors' ability to use various strategies and representations in their teaching (Magnusson, Krajcik & Borko, 1999). In physical chemistry, this may include pedagogical approaches ranging from completely instructor–centered, such as traditional lecture environments, to completely student–centered, such as active learning techniques. It also includes instructors' ability to facilitate student understanding at the macroscopic, particulate, and symbolic levels.

Finally, the fifth component of Magnusson's model of PCK is knowledge of assessment in science, which involves instructors' ability to identify not only what, but how, relevant content and skills should be assessed (Magnusson, Krajcik & Borko, 1999). In physical chemistry, this may include instructors' choice of assessment strategies. Instructors should consider several aspects of assessments such as formative or summative, individual or group, multiple choice or open–ended, conceptual or procedural, and the type of cognitive process. This component of PCK was investigated in the assessment analysis, found in Chapter 4, and will not be a focus of this study.

5.2.2. Barriers to Conducting Pedagogical Content Knowledge Research

As models of PCK were developed research regarding the PCK of educators expanded, with the primary goal to identify and help expand their PCK. Such research was more prominent at the K–12 setting compared to higher education. Limited research, and consequently limited growth of the PCK of undergraduate instructors, was hindered by three main barriers including hiring practices, beliefs about student learning, and the perception that teaching is not as important as research.

Traditionally, instructors are hired based on their expertise in a particular discipline, with limited emphasis on an instructor's expertise of learning theories or pedagogy (Light, 1974). The large research component of faculty positions is often the motivation for such hiring practices. Also, the valuation of research success over teaching success for the attainment of tenure does not encourage faculty to develop their pedagogical knowledge. Consequently, instructors often have strong content knowledge but weaker pedagogical knowledge, and therefore limited PCK.

Beliefs about student learning have also hindered research on the PCK of instructors. Many instructors are hesitant to accept responsibility when students struggle to understand course topics, and instead place blame on the students. For example, instructors were found to believe that students' passivity and poor college preparation have a greater impact on their learning than the efforts of the instructor (Gottfried et al., 1993). If instructors are unaware of their own instructional limitations, and instead focus on the limitations of their students, there is minimal motivation for instructors to further develop their PCK (Lenze & Dinham 1994).

Finally, the perception that teaching is less worthy than research is perhaps the greatest barrier to increased research and growth of the PCK of instructors. While research can be conducted to identify the current state of PCK of instructors, in order to transform their PCK, instructors must believe in the value of such efforts. This valuation, however, can be hindered by faculty's scientific professional identity (Brownell & Tanner, 2012). For example, faculty training cultivates a stronger research identity than teaching identity. Also, scientists are often afraid to identify as an educator for fear it will diminish their prestige as a researcher. Furthermore, the professional culture of science considers teaching to be a lower status than research. This last reason is further exemplified in the saying, "those who can, do; those who can't, teach," which is particularly fitting to the current valuation of teaching at colleges and universities. Further efforts are needed to combat these perceptions and help advance the PCK of instructors.

5.2.3. Pedagogical Content Knowledge Research for Science Instructors

Given the barriers discussed above, there are minimal studies that have investigated the PCK of undergraduate instructors. In four studies that have investigated the PCK of undergraduate science instructors, each study adopted a different model of PCK. The PCK models adopted for these studies ranged from Shulman's original model of PCK (Jang, 2010) to Magnusson's adaptation of PCK for science instruction (Padilla & Van Driel, 2011). Another study used the Loughran model (Padilla, Ponce-de-León, Rembado & Garritz, 2008), while the researchers of another study pooled components of different models of PCK to create their own model (Jang, Tsai & Chen, 2013). Given the diverse use of PCK models, there is not a consensus regarding the most appropriate model of PCK for undergraduate chemistry education.

While the models of PCK varied, the overarching purpose of these studies was to analyze the PCK of instructors. For example, one study examined the PCK of chemistry instructors in the context of how instructors taught the concepts of mass, moles, and molecules (Padilla, Ponce-de-León, Rembado & Garritz, 2008). The purpose of this study was not to discover implications for teaching, but instead demonstrate that the PCK of a specific topic can be investigated. Another study compared the PCK of novice and experienced physics instructors, and found that novice instructors focused on definitions of concepts while experienced instructors emphasized real world applications (Jang, 2010; Jang, Tsai & Chen, 2013). This suggests that experienced instructors have a stronger PCK compared to novice instructors, however this result is constrained to the small sample size of the study.

The purpose of this study was to broaden the landscape of research regarding the PCK of undergraduate science instructors, in particular physical chemistry instructors. This study aimed to not only describe the PCK of physical chemistry instructors, but to use those descriptions to suggest implications for teaching and targeted professional development opportunities.

5.3. Methodology

5.3.1. Collection of Data

This study adopted a multiple–case study methodology where the case is an instructor and the phenomenon are the reflections of the instructor (Yin, 2014). Six instructors of physical chemistry volunteered to participate in the study. These six instructors also participated in the nationwide survey, found in Chapter 3, and the assessment analysis, found in Chapter 4.

Due to the large physical distance separating the researcher and the participants, all data was collected electronically. Instructors completed a reflection on a biweekly basis throughout an entire semester. This repetitive reflection process helped instructors provide more comprehensive reflections. Instead of attaining a reflection at a given time point, when instructors may be more or less willing to provide detailed reflections, or when instructors may be more or less satisfied with their teaching efforts, repeated reflections provided a means to capture a more comprehensive PCK of instructors. The reflection questions are listed in Table 5.1.

Table 5.1
Instructor Reflection Questions

Question	PCK Component
1. What does being an instructor of physical chemistry mean to you?	Orientation towards science teaching
2. How do you decide what to teach and what not to teach?	Knowledge of science curriculum
3. How do you know students are learning in your physical chemistry classroom?	Knowledge of student’s understanding of science
4. How do you engage students in your physical chemistry classroom?	Knowledge of instructional strategies in science
5. Please describe successful teaching moments.	
6. Please describe challenging teaching moments.	
7. What would you like to change in the future?	

Due to the scientific nature of physical chemistry, Magnusson’s model of PCK, which was developed specifically for science instruction, was selected for this study (Magnusson, Krajcik & Borko, 1999). The first four reflection questions are associated with a PCK component (Table 5.1). Question one asks instructors to describe what it means for them to teach physical chemistry, which is related to their orientation towards science teaching. Question two asks instructors to describe how they make curricular decisions, which is related to their knowledge of science curriculum. Question three asks instructors to describe how they know that their students are learning, which is related to their knowledge of students' understanding of science. Question four asks instructors describe how they engage students in their classroom, which is related to their knowledge of instructional strategies in science.

The last three reflection questions are associated with instructor descriptions of successful teaching moments, challenging teaching moments, and proposed changes (Table 5.1). The purpose of the last three questions was to associate instructor perceptions with components of their PCK.

5.3.2. Analysis of Data

The reflection questions were analyzed through a combination of axial and open coding (Cohen, Manion & Morrison, 2011) using the qualitative data analysis software, NVivo (NVivo, 2014). Axial codes were predetermined codes and were separated into two groups. The first group of axial codes represent instructors' PCK (Magnusson, Krajcik, and Borko, 1999). The axial codes in the first group include orientation towards science teaching, knowledge of science curriculum, knowledge of students' understanding of science, and knowledge of instructional strategies in science. The second group of axial codes represent instructor perceptions of their performance in the classroom. The axial codes in the second group include successful teaching moments, challenging teaching moments, and proposed changes.

The axial codes were predetermined, prior to reading any of the reflections, because a goal of this study was to develop a rich description of instructors' PCK within the context of instructor perceptions of successful teaching moments, challenging teaching moments, and proposed changes. Beyond the axial codes, the reflections were further analyzed via open coding. Open codes were codes that emerge as the reflections were analyzed. The purpose of open coding was for the reflections to direct the development of non–predetermined codes. The following subsections contain descriptions and examples of the open codes.

5.3.2.1. Instructors' Orientation Towards Science Teaching

Instructors' orientation towards science teaching contains two components: the purpose of the instructor and the purpose of the course (Table 5.2).

Table 5.2
Instructors' Orientation Towards Science Teaching

Component	Description	Example from Reflections
Purpose of Instructor		
Facilitate Understanding	Supporting student growth through effective and adaptable teaching approaches.	"I need to be creative in how I engage students and design activities."
Inspire Students	Engaging students around interests or issues and conveying passion.	"I love inspiring young, inquisitive minds with the strange world of quantum mechanics."
Purpose of Course		
Fundamentals	Developing an understanding of the fundamental laws of nature.	"Help students understand the fundamental behavior of the universe."
Mathematics and Chemical Phenomena	Using mathematics to describe chemical phenomena.	"Provide a mathematical framework to explain concepts."

The purpose of the instructor consists of two subcomponents. First, to facilitate student understanding of concepts and skills, and second, to inspire and engage students through the course topics. The purpose of the course also consists of two subcomponents. First, to develop an understanding of the fundamentals of physical chemistry, and second, to apply mathematics to understand chemical phenomena.

5.3.2.2. Instructors' Knowledge of Science Curriculum

Instructors' knowledge of science curriculum contains two components: content and materials (Table 5.3).

Table 5.3
Instructors' Knowledge of Science Curriculum

Component	Description	Example from Reflections
Content		
Foundation	The selection of traditional topics or topics that are needed for future coursework.	"I choose topics that are standard to a physical chemistry class."
Pace and Degree of Coverage	The allocation of time to various topics.	"The students decide how quickly I lecture and what ancillary topics are presented."
Order of Topics and Connections between Topics	The organization of topics to create explicit connections.	"I try to connect new material with concepts students already learned."
Applications and Examples	The incorporation of relevant applications and meaningful examples.	"I try to include examples that are interesting and relevant."
Materials		
Textbook	The selection and usage of a textbook.	"I mostly use the textbook as a guide for what to teach."
Technology	The incorporation of technology to explain topics or solve problems.	"I use Mathematica to solve complex problems more quickly."

Instructors' knowledge of content is divided into four subcomponents. First, foundational or traditional topics can influence the decisions regarding course content. Second, instructors must consider the pace at which they cover topics, which then impacts the degree to which certain topics are covered. Third, instructors must decide the order to present topics so that connections between topics can be created. Finally, instructors may incorporate applications or examples to make the content more applicable or meaningful. Instructors' knowledge of materials is divided into two subcomponents. First, instructors select a textbook, as well as how closely their curriculum follows the textbook. Second, instructors may use technology to convey or enhance course content.

5.3.2.3. Instructors' Knowledge of Students' Understanding of Science

Instructors' knowledge of students' understanding of science contains two components: prerequisite knowledge and misconceptions, and diverse backgrounds and learning styles (Table 5.4). The former entails the identification of necessary prerequisite knowledge and the disruption of potential misconceptions. The latter involves the awareness of and ability to support the diverse backgrounds and learning styles of students.

Table 5.4
Instructors' Knowledge of Students' Understanding of Science

Component	Description	Example from Reflections
Prerequisite Knowledge and Misconceptions	The identification of prerequisite knowledge and the disruption of misconceptions.	"I need to get students up to speed on their math skills."
Diverse Backgrounds and Learning Styles	The awareness of and ability to support diverse backgrounds and learning styles.	"My students are all very different and I do not have a core group of students to teach to."

5.3.2.4. Instructor’s Knowledge of Instructional Strategies in Science

Instructors’ knowledge of instructional strategies contains two components: strategies and representations (Table 5.5).

Table 5.5

Instructors’ Knowledge of Instructional Strategies in Science

Component	Description	Example from Reflections
Strategies		
Instructor–Student Interactions	Interactions between the instructor and student, such as discussion.	“Students are asking questions and answering my questions.”
Student–Student Interactions	Interactions between students, such as group work.	“Students are conversing with each other and teaching each other.”
Practice Problems and Activities	The use of problem solving and activities to apply concepts and skills.	“I emphasize problem solving.”
Active Learning and Flipped Classroom	A shift towards less instructor–talk and management to more student–talk and engagement.	“I tried the first flipped class day and it seemed to go well.”
Representations		
Symbolic	The use and analysis of symbolic or mathematical representations.	“I explain how mathematical equations relates to real phenomena.”
PNOM and Orbitals	The use and analysis of particulate nature of matter and atomic and molecular orbitals.	“I explained reduced mass by visualizing vibrating diatomics.”
Graphical	The use and analysis of graphs.	“We spend time using graphs to understand phenomena.”

Instructors’ knowledge of strategies is divided into four subcomponents. First, instructor–student interactions involve communication between the instructor and students, such as discussion. Second, student–student interactions involve communication between students, such as group work. Third, instructors may use practice problems or activities to apply course concepts and skills. Finally, instructors may utilize active learning strategies or flip their classroom to reduce instructor management and increase student ownership of their own learning. Instructors' knowledge of representations is divided into three subcomponents, where each subcomponent is a way to represent the concepts of physical chemistry. These representations include symbolic, particulate nature of matter (PNOM) and atomic and molecular orbitals, and graphical.

5.3.2.5. A Model of Instructors' Pedagogical Content Knowledge

Now that each component of PCK has been described, a comprehensive model of PCK can be presented (Figure 5.1). This model was used as a starting point to depict the PCK of each participating instructor. The model was also used to explain how instructors' descriptions of successful teaching moments, challenging teaching moments, and proposed changes were related to components of their PCK.

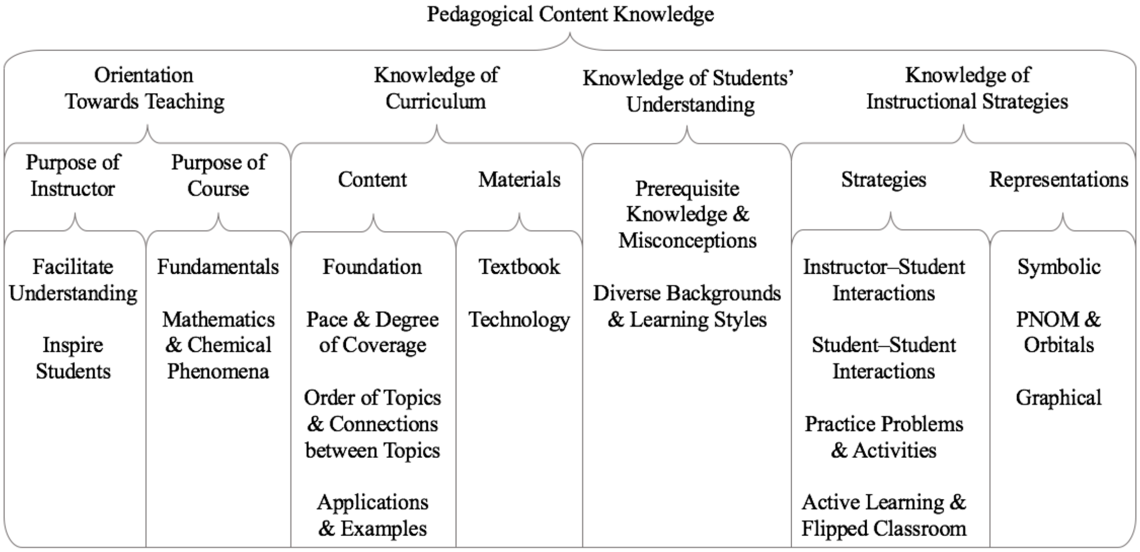

Figure 5.1. A model of pedagogical content knowledge.

When the reflections of specific instructors are discussed, pseudonyms are used to protect their anonymity and confidentiality. Pseudonyms were assigned based on the most popular names in the U.S. over the last 100 years, continuing where the assessment analysis of Chapter 4 finished (Social Security Administration, 2015). Pseudonyms reflect the gender of the instructor.

5.4. Results

The following subsections present a detailed account of the PCK for the six instructors who participated in this study. The instructors are presented in an order based on their years of professional academic experience, starting with more novice instructors and moving towards more experienced instructors.

5.4.1. Joseph's Pedagogical Content Knowledge

Joseph teaches at a medium–sized, public university in the Northeast that grants up to master's degrees in chemistry. Joseph is the most novice participating instructor with only 1–5 years of teaching experience. In the nationwide survey, Joseph reported that he dedicates about 67% of his workweek to teaching responsibilities and 11% to research endeavors, and that he adopts an instructor–centered learning environment. In the assessment analysis, it was observed that Joseph's assessment questions were predominantly subjective in nature, elicited conceptual and procedural knowledge more often than factual knowledge, and contained a greater frequency of more complex cognitive processes compared to the average. A visualization of his PCK model is found in Figure 5.2.

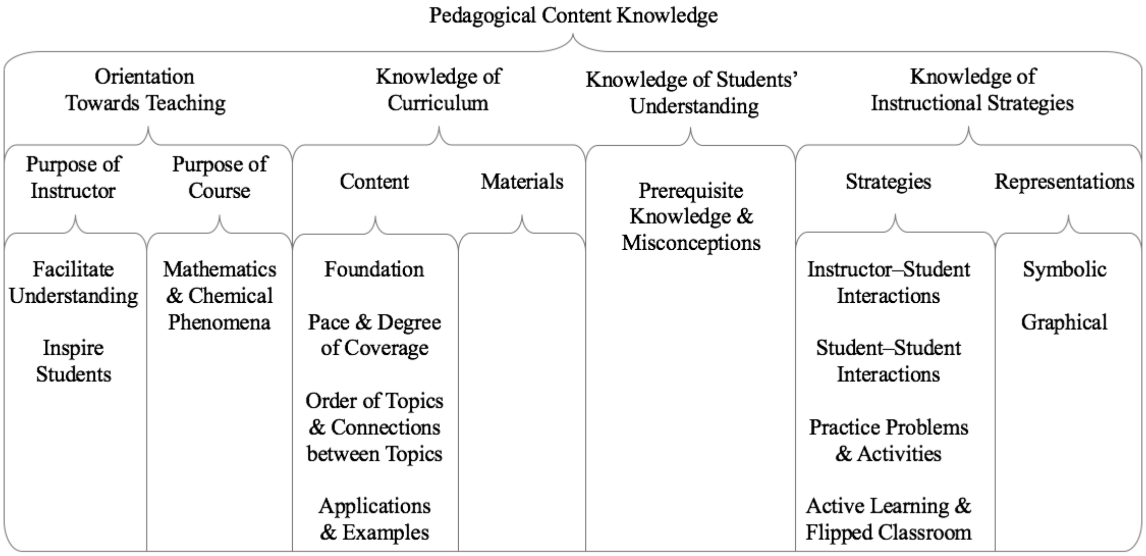

Figure 5.2. Joseph’s model of pedagogical content knowledge.

For orientation towards teaching, Joseph discussed three of the four subcomponents in his reflections. In regards to the purpose of the instructor, Joseph described his goal to facilitate understanding and inspire students, while in regards to the purpose of the course, he described his goal to use mathematics to explain chemical phenomena, but did not stress teaching the fundamentals of physical chemistry. The following two quotes highlight Joseph’s orientation towards teaching: “I want students to learn and appreciate how we can use the language of mathematics to… gain a deeper understanding of nature,” and “my job is to act as an interpreter for the math.” Based on these quotes, it is evident that Joseph views himself as an active part of the learning process, and that it is his responsibility make the mathematics as transparent as possible so that students can be inspired by the wonders of physical chemistry.

For knowledge of curriculum, Joseph discussed four of the six subcomponents in his reflections. In regards to content, Joseph considered how to pace and order topics so that both foundational knowledge and applications of that knowledge can be presented to students. In regards to materials, Joseph did not describe how a textbook or technology impact his curricular decisions. Thus, Joseph's knowledge of curriculum was based on his knowledge of content, rather than his knowledge of materials. In Joseph's orientation towards teaching, he stressed the role of mathematics. This theme carried through to his knowledge of curriculum, where his pace and degree of coverage of concepts was impacted by how he incorporated mathematics. For the ordering of topics, Joseph stated, "I initially based the curriculum on that of my predecessor. This year, I tried to reorganize content." This quote shows that while Joseph initially taught what his predecessor taught, he has now reordered topics so that one concept would logically lead to another. Joseph also incorporated examples into his teaching, exemplified by the following quote: "while making an analogy between music and quantum mechanics, several students immediately became excited and intrigued." This quote shows how Joseph strives to connect the abstract nature of quantum mechanics to the interests of his students.

For knowledge of students' understanding, Joseph discussed prerequisite knowledge and misconceptions, but not diverse backgrounds and learning styles. The role of mathematics strongly impacted Joseph's orientation towards teaching, as well as his knowledge of curriculum, and now it also impacts his knowledge of students' understanding. Joseph stated that a strong mathematics background is needed for success in physical chemistry, and that misconceptions of mathematics will hinder students' success. While Joseph is cognizant of prerequisite mathematical knowledge, he did not address how diverse learning styles may impact students' comprehension and application of mathematics.

For knowledge of instructional strategies, Joseph discussed six of the seven subcomponents in his reflections. In regards to strategies, Joseph described how instructor–student interactions are currently present in his teaching. His ability to communicate with students is exemplified in the following two quotes: “we had a lively discussion that… everyone participated in,” and “the depth and insight of questions helps me to understand how the students view different topics.” While Joseph is actively interacting with his students via his current instructional strategies, he is not currently utilizing other instructional strategies. Instead he explained how he would like to incorporate different strategies in the future. In regards to representations, Joseph described symbolic and graphical representations, but did not discuss the PNOM. Joseph’s use of symbolic language was not surprising, given that mathematics was at the forefront of his orientation towards teaching, knowledge of curriculum, and knowledge of students’ understanding. In fact, Joseph stated, “I spend lots of time trying to make the mathematics as transparent as possible.” Joseph also recognized the relevance of graphs when he stated, “I want students to… use graphs to arrive at important conclusions qualitatively.” In addition to his emphasis on mathematics, Joseph realizes the relevance of using graphs to help students develop conceptual knowledge.

When Joseph described successful teaching moments, his successes were primarily associated with mathematics and students’ understanding. In regards to mathematics, Joseph described one successful teaching moment as: “I… have finally convinced students to approach mathematical problems using a derivation approach, rather than a plug and chug approach.” This quote again exemplifies Joseph’s focus on mathematics, and shows that he strives for students to be critically aware of how to use mathematics to understand physical chemistry, rather than absentmindedly using a mathematical procedure to attain an answer. In regards to students' understanding, Joseph described another successful teaching moment as: "A student… asked a phenomenally brilliant question… she recognized that the commutator was a way to determine how the order of a series of measurements can affect the results obtained, much like the path of a process will have a profound impact on thermodynamic variables." This quote shows how interactions between Joseph and his students not only helps students deepen their comprehension, but also helps Joseph assess the current state of his students' understanding.

When Joseph described challenging teaching moments, his challenges were primarily associated with mathematics. This is not surprising given the central role mathematics has played in Joseph's PCK. One challenge Joseph described was, "while I can appreciate that the student may not have mastered calculus, I was surprised that he couldn't even recognize what is perhaps one of the most widely used symbols of calculus." This quote referenced a student's inability to identify the symbols of a derivative and a partial derivative. Joseph was frustrated because he believed that students should be able to recall such basic notation that was taught in calculus. Joseph also complained that "sloppy notation and skipping steps is lazy." This quote demonstrates Joseph's frustration when students make mistakes in conjunction with not showing all of their work.

When Joseph described what he would like to change in the future, his proposed changes were primarily associated with expanding his instructional strategies. Recall that the only instructional strategy Joseph currently uses is instructor–student interactions.

Joseph stated that he wants to “increase student engagement” but that he is not aware of how to do that. This suggests that Joseph is aware of active learning strategies, but is unsure how to incorporate such strategies. Joseph also mentioned that he may develop activities to help with students’ comprehension, but he worries that incorporating activities may slow down the pace of the course too much. Thus, Joseph acknowledges the possibility of expanding his instructional strategies, but he is uncertain of how to proceed.

In conclusion, Joseph is a novice instructor with PCK that is strongly influenced by his perception of how mathematics interacts with the teaching and learning of physical chemistry. In fact, mathematics influenced each component of Joseph’s PCK. Joseph had a robust orientation towards teaching and knowledge of curriculum, but his knowledge of materials could be expanded. For example, the use technology may provide a different approach for incorporating mathematics by solving more complex problems or visualizing solutions to problems. Joseph’s knowledge of instructional strategies could also be expanded, which was the focus of his proposed changes. This shows that as a novice instructor, Joseph is committed to personal development and growth, which will consequently broaden his PCK.

5.4.2. Mary’s Pedagogical Content Knowledge

Mary teaches at a medium–sized, public university in the South that grants up to master’s degrees in chemistry. Mary is the second most novice participating instructor with 6–10 years of teaching experience. In the nationwide survey, Mary reported that she dedicates about 70% of her workweek to teaching responsibilities and 10% to research endeavors, and that she adopts an equally instructor–centered and student–centered learning environment. In the assessment analysis, it was observed that Mary's assessment questions were predominantly subjective in nature, elicited procedural knowledge more often than factual or conceptual knowledge, and utilized cognitive processes similar to the average. A visualization of her PCK model is found in Figure 5.3.

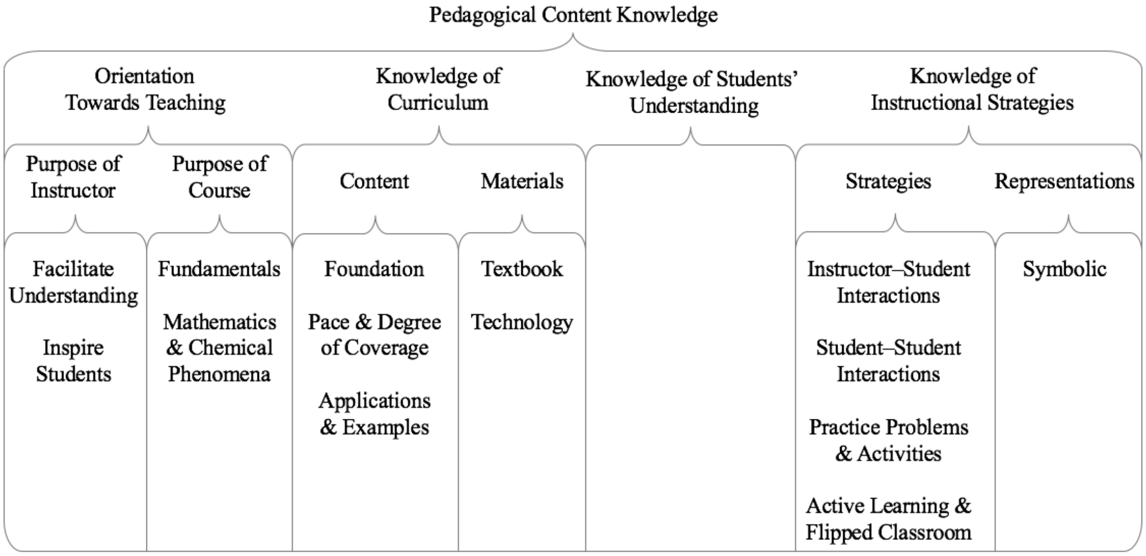

Figure 5.3. Mary's model of pedagogical content knowledge.

For orientation towards teaching, Mary discussed all four of the subcomponents in her reflections. In regards to the purpose of the instructor, Mary described her goal to facilitate understanding and inspire students, and in regards to the purpose of the course, she described her goal to introduce students to the fundamentals of physical chemistry by using mathematics to explain chemical phenomena. Mary's orientation towards teaching revolves around her role as the instructor, which is evident in the following three quotes: "sharing my love of science," "striving to get my students to think for themselves rather than to parrot back information," and "showing how mathematical models can be used to describe and predict chemical and physical behavior of chemical systems." Based on these quotes it is evident that Mary views herself as an active part of the learning process. She believes that it is her responsibility to share her love of science and to support students in the construction their own understanding.

For knowledge of curriculum, Mary discussed five of the six subcomponents in her reflections. In regards to content, Mary considered how to pace topics, but not how to order topics, so that both foundational knowledge and applications of that knowledge can be presented to students. In regards to materials, Mary stated that she used the textbook as a guide to her decisions regarding course content, which is evident in the following quote: "I try to stick to the book as much as possible, but I also pull from my past teaching and learning experiences." Thus, Mary uses the book as a starting point, but also uses past experiences to make changes when necessary. For example, Mary stated, "I teach topics that I know will be useful later on and I… connect what we are covering with the real world." Mary described how she omits some topics that are not relevant for understanding future topics, and she also strives to relate topics to meaningful, every day experiences. Mary also mentioned technology, in regards to her knowledge of materials, which is discussed in the context of her proposed changes.

Mary did not explicitly address either of the components of knowledge of students' understanding. Mary did reference the challenges students face with mathematics, but she did not explicitly connect that challenge with prerequisite knowledge and misconceptions. Much of Mary's reflections focused on active learning strategies, suggesting that she is cognizant of how students learn, but her discussion of instructional strategies was not related to diverse backgrounds and learning styles. Thus, increased knowledge of students' understanding could be an area of improvement for Mary.

For knowledge of instructional strategies, Mary discussed five of the seven subcomponents in her reflections. In regards to strategies, Mary described instructor–student interactions, student–student interactions, activities, and active learning. Not only does Mary have discussions with her students, but her students also teach each other, as evident in the following quote: "they actively participate in their group… they help one another work through problems." Mary also incorporates activities and active learning strategies, evident in the following quote: "students continue to surprise me when they solve difficult questions in their POGIL [process oriented guided inquiry learning] activities." In regards to representations, Mary mentions symbolic language, which will be discussed in the context of her challenging teaching moments, but does not discuss the PNOM or graphical representations.

When Mary described successful teaching moments, her successes were primarily associated with knowledge of instructional strategies. Mary is pleased with how her students ask good questions and work well together. The following quote describes a particularly noteworthy success: "one of my students has told me several times that she likes the way I teach, pushing them past learning by rote to understanding. She seems to like the most challenging assignments I give them the best." Thus, Mary has had success in her implementation of more student–centered instructional strategies.

When Mary described challenging teaching moments, her challenges were associated with knowledge of instructional strategies and knowledge of curriculum. While Mary noted her successes with active learning tactics, she also described the challenges. For example, Mary stated that it was challenging "getting students to buy into the the group learning." Thus, the successes of student–centered teaching efforts do not come without their challenges. Also, in terms of mathematics and the symbolic representation, Mary stated that it was challenging "getting her to see beyond the calculus to see the chemistry it describes." Finally, in regards to knowledge of curriculum, Mary struggled with the pace of topics, stating, "I find I am running out of time to cover material so I'm having to go fast to squeeze in important topics." Thus, Mary chose not to omit topics, but rather cover required topics at a faster pace.

When Mary described what she would like to change in the future, her proposed changes were associated with knowledge of instructional strategies and knowledge of curriculum. Mary currently has a robust knowledge of instructional strategies, but her knowledge is still growing because she plans to, "flip the class for more topics, and do more group work in general." Mary is also aware of how she can further develop her knowledge of curriculum, as evident in the following two quotes: "I would like to incorporate more real world examples," and "I wish I had time to find some additional visual aids or incorporate mathematical software."

In conclusion, Mary is a relatively novice instructor with a robust and growing PCK. Her strongest component of PCK, knowledge of instructional strategies, also received the most attention in her perceptions of successful teaching moments, challenging teaching moments, and proposed changes. Mary did not let the challenges of increasing student engagement shadow its successes or hinder her future efforts. One area for improvement for Mary is her knowledge of students' understanding. Given Mary's desire to expand her knowledge of curriculum and knowledge of instructional strategies, she would likely also embrace expanding her knowledge of students' understanding.

5.4.3. Charles' Pedagogical Content Knowledge

Charles teaches at a small, private university in the Northeast that grants up to bachelor's degrees in chemistry. Charles has more professional academic experience than Joseph and Mary with 11–15 years of teaching experience. In the nationwide survey, Charles reported that he dedicates about 80% of his workweek to teaching responsibilities and 10% to research endeavors, and that he adopts a student–centered learning environment. In the assessment analysis, it was observed that Charles' assessment questions contained approximately half objective and half subjective formatting, and utilized types of knowledge and types of cognitive processes similar to the average. A visualization of his PCK model is found in Figure 5.4.

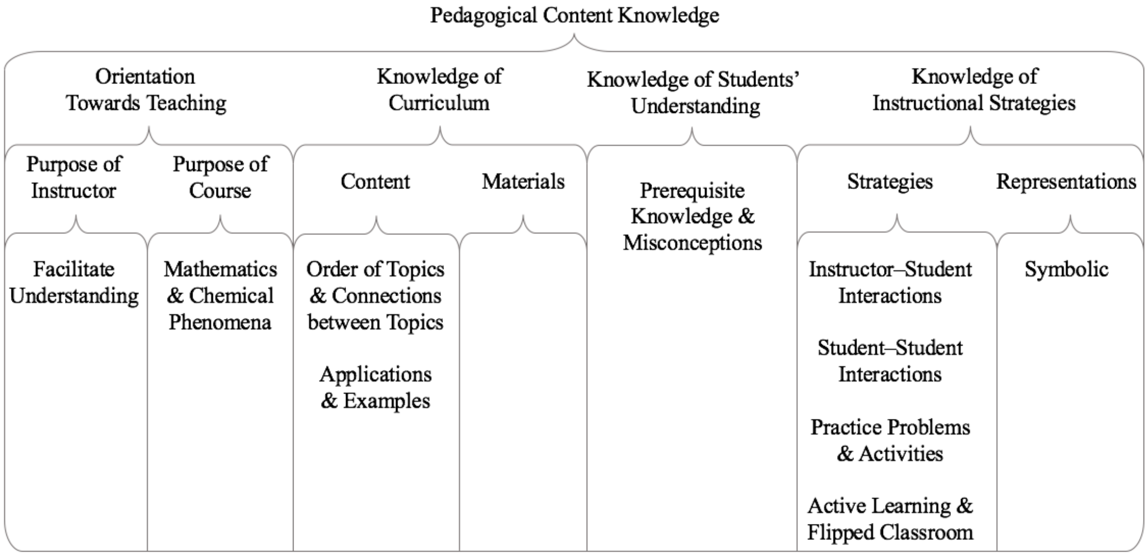

Figure 5.4. Charles' model of pedagogical content knowledge.

For orientation towards teaching, Charles discussed two of the four subcomponents in his reflections. In regards to the purpose of the instructor Charles described his goal to facilitate understanding, but did not discuss his efforts to inspire students. In regards to the purpose of the course, Charles described his goal to use mathematics to explain chemical phenomena, but did not stress the importance of teaching the fundamentals of physical chemistry. Charles' orientation towards teaching is represented in the following quote: "I provide students with the opportunity to learn how to apply mathematical models to the study of chemistry." Thus, he views himself as a provider of knowledge and translator between mathematics and chemistry.

For knowledge of curriculum, Charles discussed only two of the six subcomponents in his reflections. In regards to content, Charles discussed the ordering of topics and inclusion of applications, which will be discussed in the context of proposed changes. In regards to materials, Charles did not describe the role of a textbook or technology. Thus, Charles' knowledge of curriculum is limited, and could be an area of improvement.

For knowledge of students' understanding, Charles discussed prerequisite knowledge and misconceptions, but did not discuss diverse backgrounds and learning styles. Charles stated, "students had difficulty recalling material from previous classes." He also stated that he is tired of "correcting algebra mistakes." Thus, Charles is aware of necessary prerequisite knowledge, and acknowledges the not all students have sufficient prerequisite knowledge, but he does not propose how this issue may be overcome. If Charles considered the diverse backgrounds and learning styles of his students, such knowledge may impact how he addresses issues of inadequate prerequisite knowledge.

For knowledge of instructional strategies, Charles discussed five of the seven subcomponents in his reflections. In regards to strategies Charles described instructor–student interactions, student–student interactions, activities, and active learning. In addition to Charles interacting with students, students also help each other during class activities, as evident in the following quote: “students are conversing with each other and teaching each other.” In regards to representations, Charles discussed symbolic language, which is evident in his frustration with students’ lack of mathematical ability. Charles did not discuss the PNOM or graphical representations.

When Charles described successful teaching moments, his successes were associated with knowledge of students’ understanding and knowledge of instructional strategies. Charles was excited when “students were finally able to set up and solve an expectation value integral without much assistance,” which is evidence of students’ understanding. He was also happy when “student groups corrected their own mistakes while working through an activity,” which is evidence of successful active learning strategies.

When Charles described challenging teaching moments, his challenges were primarily associated with mathematics. Charles stated, “it is difficult for students to go through derivation after derivation and remember that they are important.” Here, Charles acknowledges the cumbersome role mathematics can play in physical chemistry, but does not offer ideas for how he could alleviate the issue.

When Charles described things he would like to change in the future, his proposed changes were associated with knowledge of curriculum and knowledge of instructional strategies. In regards to knowledge of curriculum, Charles stated, “I may move spectroscopy back with the model systems so students see immediate applications." This shows that Charles considers how the order of topics impacts students' abilities to make connections and relate material to real world applications. In regards to knowledge of instructional strategies, Charles stated that "I'm thinking about ways to make the classroom more student–centered." This shows that Charles is interested in increasing student engagement and independence, but it uncertain how to adopt such strategies.

In conclusion, Charles is a moderately experienced instructor with a stronger knowledge of instructional strategies compared to his orientation towards teaching, knowledge of curriculum, and knowledge of students' understanding. Charles currently implements instructional strategies that increase student engagement, and he plans to continue focusing on student–centered strategies moving forward with his teaching efforts. Charles' knowledge of instructional strategies may be further enhanced if he also worked to broaden other components of his PCK. For example, increased knowledge of curriculum may help Charles organize or select topics for student activities. Also, increased knowledge of students' understanding may help Charles more effectively implement instructional strategies by keeping students' diverse abilities at the forefront.

5.4.4. Patricia's Pedagogical Content Knowledge

Patricia teaches at a small, private university in the Northeast that grants up to bachelor's degrees in chemistry, and she has 11–15 years of teaching experience. In the nationwide survey, Patricia reported that she dedicates about 70% of her workweek to teaching responsibilities and 30% to research endeavors, and that she adopts an instructor–centered learning environment. In the assessment analysis, it was observed that

Patricia's assessment questions were predominantly subjective in nature, elicited conceptual and procedural knowledge more often than factual knowledge, and utilized more complex cognitive processes slightly more often compared to the average. A visualization of her PCK model is found in Figure 5.5.

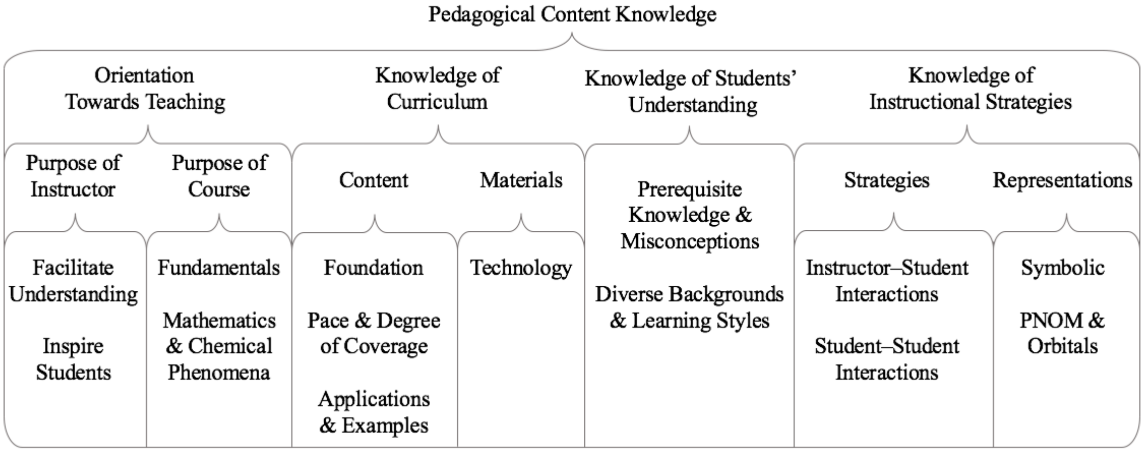

Figure 5.5. Patricia's model of pedagogical content knowledge.

For orientation towards teaching, Patricia discussed all four of the subcomponents in her reflections. In regards to the purpose of the instructor, Patricia described her goal to facilitate understanding and inspire students, and in regards to the purpose of the course, she described her goal to introduce students to the fundamentals of physical chemistry by using mathematics to explain chemical phenomena. Patricia's orientation towards teaching is evident in the following three quotes: "inviting students to challenge themselves, "helping them [students] to wonder about the molecular world," and "teaching foundational knowledge and… using mathematical tools to synthesize concepts." Based on these quotes it is evident that Patricia has a rich orientation towards teaching that encompasses various aspects of her goal as the instructor, as well as the goal of the course itself.

For knowledge of curriculum, Patricia discussed four of the six subcomponents in her reflections. In regards to content, Patricia considered how to pace topics, but not how to order topics, so that both foundational knowledge and applications of that knowledge can be presented to students. Her knowledge of content is summarized in the following two quotes: “time constraints become an issue so I go with the material that graduate programs or future employers would expect chemistry majors to know,” and “I look for thematic concepts.” In regards to materials, Patricia discussed the role of technology, but not a textbook. Patricia’s knowledge of technology is discussed in the context of her knowledge of instructional strategies, as well as her successful and challenging teaching moments.

For knowledge of students’ understanding, Patricia discussed both prerequisite knowledge and misconceptions, as well as diverse backgrounds and learning styles. Patricia is frustrated when students do not have the necessary prerequisite knowledge, as described in her challenging teaching moments, but she does not discuss how the issue of inadequate prerequisite knowledge could be tackled. Patricia’s knowledge of diverse backgrounds and learning styles is evident in the following quote: “I would love to just have chemistry students and not a mixture of chemistry and biochemistry.” Patricia recognizes the differences in backgrounds and interests between chemistry and biochemistry majors, and believes that the best way to honor those differences is to have separate classes for each major.

For knowledge of instructional strategies, Patricia discussed four of the seven subcomponents in her reflections. In regards to strategies, Patricia discussed instructor–student interactions and student–student interactions, but not activities or active learning.

The interactions in her classroom are described by the following two quotes: “asking and answering questions,” and “helping peers… when they get stuck.” Thus, Patricia is communicating with her students and encouraging students to help each other, but her knowledge of instructional strategies could be broadened to include additional approaches. In regards to representations, Patricia discussed symbolic and PNOM, but not graphical representations. For example, Patricia described how “visualizing vibrational modes with Spartan” allowed students to use technology to visualize the PNOM without getting lost in the mathematics.

When Patricia described successful teaching moments, her successes were primarily associated with instructional strategies. She was happy when students “asked informed questions,” which showcases successful instructor–student interactions. Patricia was also satisfied with her incorporation of technology, which is evident in the following two quotes: “the PhET [physics education technology] simulation… prompted a very good discussion,” and “[Spartan] made the derivation of selection rules… more tangible.” These quotes show how Patricia’s incorporation of technology positively impacted student participation and understanding.

When Patricia described challenging teaching moments, her challenges were associated with knowledge of curriculum and knowledge of students’ understanding. In regards to curriculum, Patricia stated, “I don’t have a good description or visualization of the rigid rotor.” This quote demonstrates Patricia’s ability to acknowledge where her presentation of content could be improved, although she is uncertain how to make those adjustments. In regards to students’ understanding, Patricia stated, “students did not know the molecular geometry of methane, this seems so fundamental.” This quote demonstrates

Patricia's frustration when students are unable to recall basic information from general chemistry.

When Patricia described things she would like to change in the future, her proposed changes were associated with knowledge of curriculum and knowledge of instructional strategies. In regards to curriculum, Patricia stated, "I would love to connect [topics] to more applications that students relate to." This demonstrates Patricia's desire to make the topics of physical chemistry more relatable and meaningful for students. In regards to instructional strategies, Patricia stated that she would like to do "less lecturing." Here, Patricia hints at the idea of incorporating more student–centered teaching approaches, but she does not discuss specific strategies.

In conclusion, Patricia is a moderately experienced instructor with a stronger orientation towards teaching and a weaker knowledge of instructional strategies. Patricia is able to clearly articulate her goals as an instructor, as well as the purpose of the course, but he repertoire of instructional strategies is limited. Although Patricia stated that she plans to lecture less often in the future, her plans may benefit from an increased knowledge of instructional strategies. Patricia also discussed technology across several components of her PCK, and her use of technology incorporated multiple representations which enhanced student understanding and stimulated discussion.

5.4.5. Thomas' Pedagogical Content Knowledge

Thomas teaches at a large, public university in the Midwest that grants doctorate degrees in chemistry. Thomas is one of the most experienced participating instructors with over 20 years of teaching experience. In the nationwide survey, Thomas reported that he dedicates about 15% of his workweek to teaching responsibilities, 10% to research endeavors and the remaining 85% to other responsibilities, and that he adopts an instructor–centered learning environment. In the assessment analysis, it was observed that Thomas' assessment questions were predominantly subjective in nature, elicited procedural knowledge more often than factual or conceptual knowledge, and used the cognitive processes of remembering and applying less and more often compared to the average, respectively. A visualization of his PCK model is found in Figure 5.6.

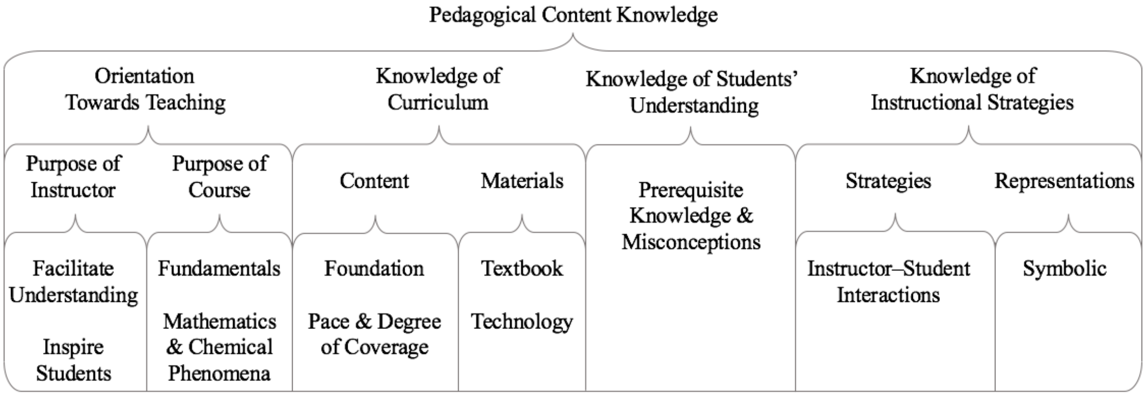

Figure 5.6. Thomas' model of pedagogical content knowledge.

For orientation towards teaching, Thomas discussed all four of the subcomponents in his reflections. In regards to the purpose of the instructor, Thomas described his goal to facilitate understanding and inspire students, and in regards to the purpose of the course, he described his goal to introduce students to the fundamentals of physical chemistry by using mathematics to explain chemical phenomena. Thomas' orientation towards teaching is evident in the following two quotes: "it means serving as a conduit of knowledge for my students, all of the information is out there, but I serve as a catalyst to get the knowledge out there and inside the brains of my students," and "trying to inspire students to understand how mathematical models apply to chemistry." Based on these quotes it is evident that Thomas views himself as an active part of the learning process, and believes that it is his responsibility to inspire and support students.

For knowledge of curriculum, Thomas discussed four of the six subcomponents in his reflections. In regards to content, Thomas considered how to pace foundational topics, but not how to order topics, or how to incorporate applications of topics. In regards to materials, Thomas discussed both the role of the textbook and technology, with the latter described in the context of his proposed changes. Thomas' knowledge of curriculum is exemplified in the following quote: "generally, I follow the book and cover what I think is important, skipping as necessary to keep up with a projected number of topics." Thus, Thomas' knowledge of curriculum is influenced by the textbook, although he realizes that there is not sufficient time to cover everything in the textbook.

For knowledge of students' understanding, Thomas discussed prerequisite knowledge and misconceptions, but not diverse backgrounds and learning styles. Thomas acknowledged the need for "getting students up to speed on their math skills," but he did not describe how this could be accomplished. If Thomas considered students' diverse background and learning styles he may gain insight on how to help students attain the necessary prerequisite knowledge.

For knowledge of instructional strategies, Thomas discussed only two of the seven subcomponents in his reflections. In regards to strategies, Thomas only discussed instructor–student interactions. Such interactions are evident in the following quote, "they [students] ask relevant questions." Beyond encouraging student participation, Thomas did not incorporate additional instructional strategies. In regards to representations, Thomas discussed symbolic notation, but not the PNOM or graphical representations. Thomas' use of the symbolic representation is discussed in the context of his successful and challenging teaching moments.

When Thomas described successful teaching moments, his successes were primarily associated with mathematics. Two successful teaching moments were "when students finally learn that units are sometimes more important than numbers," and "when I see that a student understands how a mathematical equation relates to a real phenomenon." These successful teaching moments show that Thomas does not want students to apply mathematical procedures without first considering why they are performing a certain computation, as well as the real world meaning of the computation. In other words, Thomas wants students to develop conceptual mathematical knowledge, rather than procedural mathematical knowledge.

When Thomas described challenging teaching moments, his challenges were primarily associated with mathematics. For example, Thomas was frustrated with "getting students to use calculus properly." While Thomas realizes that students' mathematical abilities impact their success in physical chemistry, he does not propose a strategy for helping students bolster their understanding of and ability to apply calculus.

When Thomas described things he would like to change in the future, his proposed changes were primarily associated with mathematics. For example, Thomas stated that he would like to incorporate "more computer simulations of some of the mathematical models." Here, Thomas plans to use technology to help visualize mathematical models so that students can develop a conceptual understanding without getting lost in the computations.

In conclusion, Thomas is an experienced instructor with limited knowledge of instructional strategies and an overall PCK that is strongly influenced by his perception of mathematics. The only instructional strategy that Thomas used was instructor–student interactions, and he did not state any plans for incorporating new teaching approaches. In fact, his proposed changes, as well as his successful and challenging teaching moments, all revolved around mathematics. Thomas was satisfied when students used mathematics to extend their understanding, but was frustrated when students' mathematical ability hindered their understanding. To tackle this challenge, Thomas proposed using technology to help visualize mathematical models. While this change will likely have its benefits, Thomas should consider further developing his PCK, particularly his knowledge of instructional strategies, because teaching approaches that increase student engagement may help alleviate some of the challenges of mathematics.

5.4.6. Christopher's Pedagogical Content Knowledge

Christopher teaches at a medium–sized, public university in the Midwest that grants up to master's degrees in chemistry, and has over 20 years of teaching experience. In the nationwide survey, Christopher reported that he dedicates about 60% of his workweek to teaching responsibilities and 20% to research endeavors, and that he adopts an instructor–centered learning environment. In the assessment analysis, it was observed that Christopher's assessment questions contained approximately half objective and half subjective formatting, and utilized types of knowledge and types of cognitive processes similar to the average. A visualization of his PCK model is found in Figure 5.7.

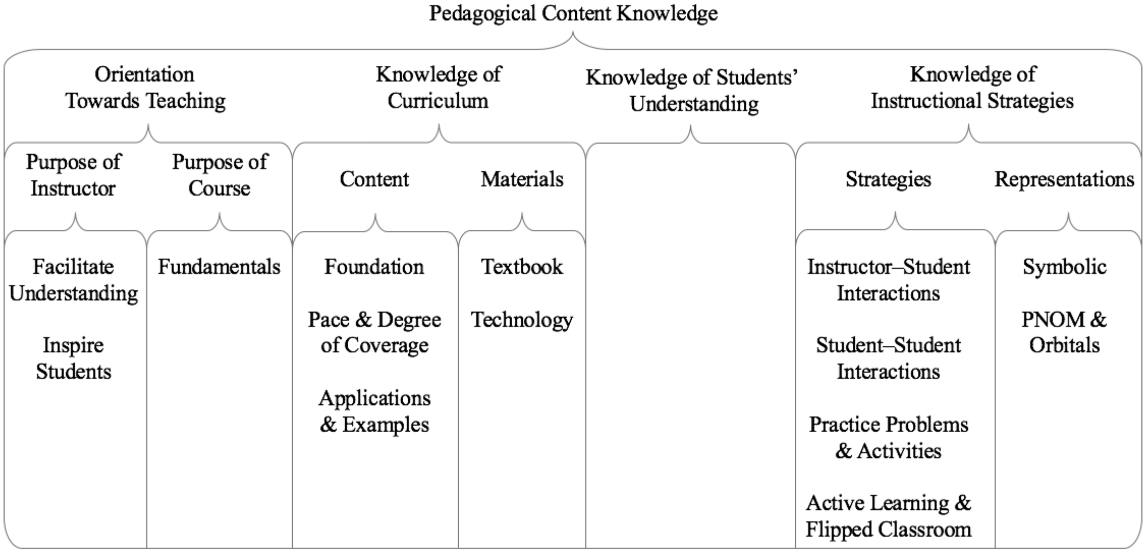

Figure 5.7. Christopher's model of pedagogical content knowledge.

For orientation towards teaching, Christopher discussed three of the four subcomponents in his reflections. In regards to the purpose of the instructor, Christopher described his goal to facilitate understanding and inspire students. In regards to the purpose of the course, Christopher described his goal to introduce students to the fundamentals of physical chemistry, but did not mention using mathematics to explain chemical phenomena. Thomas' orientation towards teaching is evident in the following three quotes: "it is the highlight of my career as a professor of chemistry," "I love inspiring young inquisitive minds by presenting the strange world of quantum mechanics," and "I really like conveying my passion… to my students, in the hopes that I might inspire a few to want to go further." Based on these quotes, it is evident that Christopher has a passion for teaching, and that passion is central to his orientation towards teaching.

For knowledge of curriculum, Christopher discussed five of the six subcomponents in his reflections. In regards to content, Charles considered how to pace topics, but not how to order topics, so that both foundational knowledge and applications of that knowledge can be presented to students. In regards to materials, Charles discussed the role of the textbook and technology. The latter is discussed on the context of his instructional strategies. Overall, Charles' knowledge of curriculum is exemplified in the following two quotes: "I follow the textbook very closely, but realize I can't cover everything mentioned in the text, so I try to hit the highlights," and "relating the particle in a box wave function to vibrations on a guitar string." Charles follows the textbook, but acknowledges the need to omit material so that there is ample time to cover more relevant topics. He also relates concepts to everyday objects so that the abstract nature of quantum mechanics can become more meaningful.

For knowledge of students' understanding, Christopher did not discuss prerequisite knowledge and misconceptions or diverse backgrounds and learning styles. Thus, knowledge of students' understanding could be an area of improvement for Christopher.

For knowledge of instructional strategies, Christopher discussed six of the seven subcomponents in his reflections. In regards to strategies, Christopher discussed instructor–student interactions, student–student interactions, activities, and active learning, where the former two strategies are currently enacted and the latter two strategies are discussed in the context of his proposed changes. Interactions among Charles and his students, as well as the incorporation of technology, are evident in the following two quotes: "they ask good questions," and "when they are all helping each other solve the clicker questions." Thus, Charles encourages student participation, which is facilitated through the use of clickers. In regards to representations, Charles discussed symbolic and PNOM, but not graphical representations. For example, Charles "showed the class the actual computed molecular orbitals of a molecule." This use of technology allowed students to visualize molecular orbitals without getting lost in the computations.

When Christopher described successful teaching moments, his successes were primarily associated with knowledge of instructional strategies. Christopher was proud to see "students help each other" and he was also satisfied when "students were very excited and interested and asked lots of questions." Thus, Christopher was satisfied with student engagement and participation.

When Christopher described challenging teaching moments, his challenges were primarily associated with knowledge of students' understanding. Christopher was frustrated by "getting dumb questions." Despite encouraging student participation, Christopher found it challenging to address "dumb" student questions. Christopher should be cautious how he responds to these questions, because the nature of his response may limit student participation in the future.

When Christopher described things he would like to change in the future, his proposed changes were primarily associated with knowledge of instructional strategies. Christopher stated that he "would like to see more student–student interactions." To accomplish this, he proposed that he may "invert the classroom someday" and then "work more problems instead of straight lecture." Thus, Christopher sees value in broadening his knowledge of instructional strategies.

In conclusion, Christopher is an experienced instructor with an evolving PCK, specifically knowledge of instructional strategies. Christopher currently uses instructor–student interactions and student–student interactions, but he would like to adopt additional teaching approaches to increase student engagement and shift the class from a lecture environment to a problem solving environment. Christopher is an example of an experienced instructor who is not only willing to make changes, but also actively seeking out means to improve his teaching efforts.

5.5. Discussion

The analysis of reflections of physical chemistry instructors revealed characteristics of their PCK, as well as how their PCK was associated with successful teaching moments, challenging teaching moments, and proposed changes. This study is not without its limitations, however. Given the voluntary sampling, the participating instructors may not be representative of physical chemistry instructors across the country. Consequently, the PCK of the participating instructors may not be representative of the PCK of physical chemistry instructors across the country. Also, while the repeated reflection process helped alleviate this next limitation, the reflections of instructors may not be entirely descriptive, complete or honest. Despite these limitations, the analysis of individual instructors led to four trends regarding their PCK. First, instructors had a strong orientation towards teaching. Second, instructors had a varying knowledge of curriculum. Third, instructors had a weak knowledge of students' understanding. Fourth, instructors had an evolving knowledge of instructional strategies.

The strongest PCK component was orientation towards teaching. Instructors provided rich descriptions for both the purpose of the instructor and the purpose of the course. Instructors viewed themselves as a mechanism to facilitate student understanding, as well as a source for student inspiration. Instructors also stated the importance of teaching the fundamentals of physical chemistry, as well as using mathematics to explain those fundamentals. Instructors' robust orientation towards teaching transcended different types of institutions and teaching experiences, and may be due to instructors' strong content knowledge.

The most variable PCK component was knowledge of curriculum. While the majority of instructors discussed how they teach topics that are foundational to physical chemistry, need to address issues of time in regards the pace and degree of coverage of course material, and incorporate meaningful applications and examples, very few instructors discussed how topics could be organized to facilitate building connections between topics. Some instructors described how their selected textbook influenced their curricular decisions, which ranged from closely following the textbook to adapting the textbook material to best fit the needs of their course and their students. Also, some instructors incorporated technology to convey information and enhance student understanding, which ranged from visual aids to computational software. Thus, the analysis of reflections showed variability of instructors' knowledge of curriculum.

The weakest PCK component was knowledge of students' understanding. Very few instructors discussed prerequisite knowledge and misconceptions or diverse backgrounds and learning styles, and when they did, it was often in the form of a challenge or complaint. Many instructors acknowledged mathematics as a prerequisite knowledge and skill, but the instructors did not explicitly state how to assess prior knowledge or what to do if necessary prerequisite knowledge was lacking. Additionally, instructors did not discuss how to identify or disrupt misconceptions. In regards to student diversity, one instructor hinted at the different abilities and interests of chemistry and biochemistry majors, but none of the instructors critically addressed the need to honor student diversity and tailor teaching approaches to support the diverse needs of students. Thus, instructors may want to consider broadening their knowledge of students' understanding.

An evolving PCK component was knowledge of instructional strategies. All of the instructors incorporated instructor–student interactions and the majority of instructors also incorporated student–student interactions. Some instructors also utilized problem solving, activities and active learning strategies. In addition to current instructional strategies, knowledge of instructional strategies was prevalent in many instructors' descriptions of successful teaching moments and proposed changes. Instructors were proud of increasing student interest, participation, and engagement, and strived to continue, expand, and improve such efforts in the future. For instructors who currently adopt more instructor–centered approaches, many expressed interest in shifting towards more student–centered approaches but were hesitant to proceed. For instructors who currently currently adopt more student–centered approaches, many expressed interest in further developing their active learning strategies. Thus, instructors have an evolving knowledge of instructional strategies.

In conclusion, reflections were used to examine the PCK of physical chemistry instructors and to associate components of PCK to successful teaching moments, challenging teaching moments, and proposed changed. Next, implications of the analysis and discussion are presented.

5.6. Implications for Teaching

The analysis of instructor reflections showed how the PCK of instructors can be described. Moving forward, this description of PCK can help transform the PCK of instructors. This transformation can be enhanced through cycles of reflection and revision, targeted professional development opportunities, and communication and collaboration between educators and researchers.

Instructors can use a cyclic process of reflection, revision, and action to become critically aware of their current PCK, as well as transform their PCK. Through reflection, instructors can become more cognizant of the current state of their PCK, and in turn how their PCK influences their curricular and pedagogical decisions. Increased awareness may help uncover strengths and weaknesses, which may then lead to revision. Through revision, instructors can use what was uncovered via the reflection process to modify their attitudes and actions. After a change is attempted, instructors should again reflect upon its advantages and pitfalls. For example, instructors' knowledge of students' understanding was found to be the weakest PCK component. Given this observation, instructors should use the results of their reflections to revise their knowledge of students' understanding and put those revisions into action. A constant cycle of reflection, revision, and action will help instructors continually develop their PCK and evolve as educators.

Targeted professional development opportunities can help transform the PCK of instructors. Professional development opportunities should be provided so that instructors can seek help for specific areas of concern or needed improvement. For example, if one instructor has limited knowledge of students' understanding, like Mary, while another instructor has limited knowledge of instructional strategies, like Thomas, different professional development opportunities should be available so that each instructor can receive the specific help they need. Additionally, the specific information presented via professional development should be presented within a broader context so that instructors can develop a specific area of need, as well as learn how that need fits within the broader context of teaching.

Communication and collaboration between educators and researchers can help transform the PCK of instructors. Educators should share their teaching efforts with each other so that instructors can gain new ideas or learn from someone's mistakes. Researchers should also reach out to help educators because given the diverse interests and skills sets of researchers and educators, the combination of their unique abilities may better support student learning. Ultimately, the future of physical chemistry education will be best supported by continued collaboration and communication between educators and researchers.

6. Conclusion

6.1. Overarching Findings

This dissertation contains three distinct, yet related, studies: a nationwide survey, an assessment analysis, and reflections on teaching and learning within undergraduate physical chemistry courses.

The nationwide survey, found in Chapter 3, investigated the current state of physical chemistry education across the United States (U.S.) (Fox & Roehrig, 2015). The survey measured the depth and breadth of course content, how content is delivered and assessed, and the beliefs and experiences of instructors. In regards to content, there was a core group of thermodynamics and quantum mechanics topics that were covered by almost all instructors, however there was a larger group of topics with a wide variability of coverage. In regards to instructional strategies, the majority of instructors created an instructor–centered environment, but some instructors were moving towards more student–centered approaches. Such efforts occurred primarily at baccalaureate institutions, and were not impacted by the degree of teacher preparation experience. In regards to assessment, instructors reported giving more mathematical questions, which contradicted with their preferred conceptual learning goals. In regards to beliefs, instructors were in stronger agreement about the challenges of physical chemistry education and in weaker agreement about strategies to overcome those challenges. Overall, the nationwide survey provided a broad description of the current state of physical chemistry education.

The assessment analysis, found in Chapter 4, investigated the current state of instructor–written physical chemistry assessments. The assessment analysis examined the format, type of knowledge, and type of cognitive processes of assessments questions. In regards to format, on average, there were twice as many subjective style questions compared to objective style questions. This ratio was more extreme for baccalaureate and master's institutions and reversed for doctorate institutions. In regards to type of knowledge, there was an approximately even distribution among questions that elicited factual, conceptual, and procedural knowledge, and instructor–written physical chemistry assessments had a much higher frequency of factual questions compared to the ACS general and organic chemistry exams. In regards to type of cognitive processes, the majority of questions utilized a simpler cognitive process from the bottom half of Bloom's taxonomy. The simplest cognitive process of remembering was associated with factual knowledge, while conceptual and procedural knowledge were associated with a range of cognitive processes. The assessments of select instructors were further investigated to showcase trends, extremes, and anomalies of assessment characteristics. Overall, the assessment analysis provided a broad, quantitative description, as well as a narrower, qualitative description of instructor–written physical chemistry assessments.

The reflections on teaching and learning, found in Chapter 5, examined what instructor reflections reveal about their pedagogical content knowledge (PCK). The reflections provided a rich description of the PCK of physical chemistry instructors, and associated successful teaching moments, challenging teaching moments, and proposed changes with instructors' orientation towards teaching, knowledge of curriculum, knowledge of students' understanding, and knowledge of instructional strategies. Instructors had a strong orientation towards teaching, a varied knowledge of curriculum, a weak knowledge of students' understanding, and a constantly evolving knowledge of instructional strategies. Thus, instructors were better able to explain their role as an instructor and the purpose of the course, compared to understanding how students' construct knowledge. Also, instructors were open to attempting more student–centered instructional strategies, but were often uncertain how to proceed. Overall, the reflections on teaching and learning provided a rich description of the PCK of physical chemistry instructors.

Together, the three studies of this dissertation have helped broaden the landscape of physical chemistry education research. The diverse levels of scale, ranging from nationwide perspectives to the perspective of individual instructors, as well as diverse methodologies, including both quantitative and qualitative approaches, have served to expand and transform physical chemistry education research.

6.2. Implications for Teaching

Based on the analysis of data and discussion of themes presented in the nationwide survey, assessment analysis, and reflections on teaching and learning, there are four implications that instructors of physical chemistry should consider as they move forward with their teaching. First, instructors should state explicit learning goals. Second, instructors should design assessment materials to measure students' mastery of learning goals. Third, instructors should select instructional strategies to facilitate the mastery of learning goals. Fourth, instructors should reflect upon the appropriateness and effectiveness of their learning goals, assessment materials, and instructional strategies and implement relevant revisions.

First, instructors should identify learning goals for their course. Learning goals may consist of facts students should remember, concepts students should understand, or skills students should be able to apply. When identifying learning goals, instructors may consider what students need for future coursework or careers, or what would inspire or engage students. Instructors may also consider topics that are covered by the American Chemical Society (ACS) exams, or topics that are covered by other institutions. Ultimately, learning goals should represent what instructors want students to get out of their course.

Second, instructors should develop assessment materials to measure students' mastery of learning goals. Assessment materials should be designed after learning goals are identified so that the assessments strategies are associated with the learning goals. When developing assessment materials, instructors should consider several aspects of assessments such as formative or summative, individual or group, multiple–choice or open–ended, conceptual or procedural, and the type of cognitive process. Varying assessment strategies can be appropriate, so long as they measure students' mastery of the learning goals.

Third, instructors should select instructional strategies to facilitate the mastery of learning goals. Instructional strategies should only be selected after instructors have determined the learning goals of their course and developed assessments that measure students' mastery of learning goals. Thus, instructional strategies serve as a bridge between learning goals and assessment. The bridge cannot be built until the learning goals and assessment materials are established, the bridge will lead to the wrong place if assessment materials do not appropriately measure mastery of the learning goals, and the bridge will collapse if instructional strategies do not effectively support the mastery of learning goals.

Fourth, instructors should reflect upon their learning goals, assessment materials, and instructional strategies, and make necessary revisions. Instructors should reflect upon the appropriateness and explicitness of learning goals. They should also reflect upon the ability of their assessments to measure students' mastery of the learning goals. Next, instructors should reflect upon the ability of their instructional strategies to facilitate mastery of the learning goals. Finally, instructors should utilize what they learned from the reflection process to make necessary revisions, and then put those revisions into action. A constant cycle of reflection, revision, and action will help instructors continually evolve as educators.

Ultimately, advice for instructors as they develop a course is as follows: first, state the learning goals, second, design assessment materials, and third, plan instructional strategies. Then, instructors should critically evaluate the appropriateness of their learning goals, the ability of their assessments to measure mastery of learning goals, and the effectiveness of their instructional strategies to support students' mastery of learning goals via a cycle of reflection, revision and action.

6.3. Future Work

Moving forward, there are several directions for further research. Five potential directions are discussed here. First, classroom observations can be conducted. Second, student participation can be incorporated. Third, targeted professional development opportunities can be created. Fourth, research can be expanded to other areas of chemistry and to graduate education. Fifth, continued collaboration and communication among chemists, educators, and researchers can be enhanced.

First, classroom observations can be conducted. This dissertation worked with physical chemistry instructors from across the U.S., and the large physical distance between the researcher and the participants hindered the ability to conduct classroom observations. To expand the three studies of this dissertation, however, classroom observations could be conducted. Classroom observations would require permission from the instructor and students, and the researcher's location and time availability would impact the number of participants, as well as how frequently a participant could be observed. Assuming classroom observations could be successfully and amply scheduled, they would provide a new perspective for physical chemistry education research. For example, classroom observations could allow comparisons to be made between how instructors perceive their teaching efforts with how those efforts are actually enacted in the classroom.

Second, student participation can be incorporated. This dissertation focused on the perspective of the instructor, not the student, however future research could incorporate student participation. While investigating the attitudes and actions of instructors is vital, especially given their autonomy and independence in undergraduate education, adding the student voice would provide a new perspective for physical chemistry education research. Including students in the research design would allow student perceptions of physical chemistry, student perceptions of their instructor, and student performance in physical chemistry to be investigated. This may allow comparisons to be made between how instructors and students perceive what happens in a physical chemistry classroom.

Third, focused professional development opportunities can be designed and administered. Targeted professional development opportunities should be provided so that instructors can seek help for specific areas of concern or desired improvement. Research can then be conducted on the ability of the professional development to enhance the educational efforts of instructors. Such research should evaluate the impacts of the professional development at several time points so that immediate and long term ramifications can be identified.

Fourth, current efforts to improve the teaching and learning of physical chemistry can be expanded to include other chemistry disciplines. For example, while general and organic chemistry are highly researched in the field of chemical education, inorganic and analytical chemistry, like physical chemistry, are far under researched in comparison. Additionally, chemical education research has a greater focus on undergraduate education, compared to graduate education. While a greater number of students enroll in undergraduate chemistry courses, the students who choose to pursue graduate studies in chemistry should not be subjected to diminished educational practices. Thus, research regarding the teaching and learning of upper level undergraduate chemistry courses, as well as graduate courses, could be the focus of future work.

Ultimately, future research regarding undergraduate and graduate chemistry education will be best supported by continued collaboration and communication among chemists, educators, and researchers. While individuals typically do not identify solely as a chemist, educator, or researcher, they do embody a unique set of strengths and weaknesses. For example, some individuals may focus greater efforts towards teaching or research, and consequently have diverse interests and skill sets. Also, the research areas of individuals may be experimental, computational, or educational, again resulting in diverse interests and skills sets. Therefore, the unique abilities of chemists, educators, and researchers should be valued and utilized in order to continually strive for outstanding chemistry education.

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Appendix 1. Physical Chemistry Survey

1. How many years of experience do you have teaching physical chemistry?
    - 1–5
    - 6–10
    - 11–15
    - 16–20
    - More than 20

2. What area of research best describes your work?
    - Theoretical Chemistry
    - Experimental Chemistry
    - Equally Theoretical and Experimental Chemistry

3. What percent of your work week is spent doing the following? The percentages should sum to 100.
    - Teaching Responsibilities
    - Research Responsibilities
    - Other

4. At your college or university, is the course content for Physical Chemistry approximately divided into one semester of Thermodynamics, Kinetics, and Statistical Mechanics, and one semester of Quantum Mechanics and Spectroscopy?
    - Yes
    - No. If no, please describe the organization of physical chemistry below.

5. At your college or university, what course of Physical Chemistry must be taken first?
    - Thermodynamics, Kinetics, and Statistical Mechanics
    - Quantum Mechanics and Spectroscopy
    - Either section can be taken prior to the other

6. What undergraduate Physical Chemistry courses do you teach? Please check all that apply.
    - Thermodynamics, Kinetics, and Statistical Mechanics
    - Quantum Mechanics and Spectroscopy
    - Other

7. What textbook do you use?

8. If you teach Thermodynamics, Kinetics, and Statistical Mechanics, to what extent are the following topics covered (not at all, moderate degree, great degree) and what type of student understanding is expected (mathematical, conceptual, both)? If you answer "Not at all" to the first question, you do not need to answer the second question.
    - Properties of Gases
    - Boltzmann Factor
    - Partition Functions
    - First Law of Thermodynamics
    - Second Law of Thermodynamics
    - Third Law of Thermodynamics
    - Helmholtz and Gibbs Energies
    - Phase Equilibria
    - Liquid–Liquid Solutions
    - Solid–Liquid Solutions
    - Chemical Equilibria
    - Kinetic Theory of Gases
    - Rate Laws
    - Reaction Mechanisms
    - Reaction Dynamics
    - Solids and Surface Chemistry

9. If you teach Quantum Mechanics and Spectroscopy, to what extent are the following topics covered (not at all, moderate degree, great degree) and what type of student understanding is expected (mathematical, conceptual, both)? If you answer "Not at all" to the first question, you do not need to answer the second question.
    - History of Quantum Mechanics
    - Classical Mechanics
    - Postulates of Quantum Mechanics
    - Free Particle
    - Particle in a Box
    - Harmonic Oscillator
    - Rigid Rotator
    - Hydrogen Atom
    - Approximation Methods
    - Multielectron Atoms
    - Diatomic Molecules
    - Polyatomic Molecules
    - Computational Methods

- Symmetry and Group Theory
- Molecular Spectroscopy
- Laser Spectroscopy

10. What type of discourse is established during class?
    - Instructor led discourse
    - Student led discourse
    - Equally instructor and student led discourse

11. What percent of your exams consist of the following types of questions? The percentages should sum to 100.
    - Objective Questions (multiple choice, true or false, matching)
    - Subjective Questions (word problems, math problems, free response questions)

12. What percent of your exams consist of the following types of questions? The percentages should sum to 100.
    - Conceptual Questions
    - Mathematical Questions

13. What is a typical final grade distribution? The percentages should sum to 100.
    - A
    - B
    - C
    - D
    - F
    - Withdrawal

14. Have you ever participated in any form of teacher training? If so, please describe your experiences below.

15. Please describe how students struggle to understand physical chemistry, and how student understanding of physical chemistry may be improved.

16. Please describe what you enjoy, and do not enjoy, about teaching physical chemistry.

Thank you for completing the survey! If you would like to participate in a follow up survey or interview, please provide your contact information below.

17. What is your full name?

18. What is your email address?

19. At which college or university are you currently employed?

Appendix 2. Follow Up Physical Chemistry Survey

1. Compared to other physical chemistry courses at ACS certified institutions, how similar or different do you think your physical chemistry course is?
    - Very similar
    - Somewhat similar
    - Somewhat different
    - Very different

2. How similar or different do you think physical chemistry courses at ACS certified institutions should be?
    - Very similar
    - Somewhat similar
    - Somewhat different
    - Very different

3. Who is responsible for successful student understanding of physical chemistry?
    - The student is completely responsible.
    - The student is mostly responsible and the instructor is slightly responsible.
    - The student and instructor are equally responsible.
    - The instructor is mostly responsible and the student is slightly responsible.
    - The instructor is completely responsible.

4. Please rank the following statements regarding why students struggle to understand physical chemistry, where 1 is the most relevant statement and 6 is the least relevant statement. To change the ranking, please click and drag the most relevant statement to the top and the least relevant statement to the bottom.
    - Students struggle because they lack the necessary mathematics background.
    - Students struggle because they lack the necessary physics background.
    - Students struggle to understand the concepts of physical chemistry.
    - Students struggle to make connections between the concepts and mathematics of physical chemistry.
    - Students struggle because they do not put forth the effort needed to understand physical chemistry.
    - Students struggle because physical chemistry is a challenging course.

5. Please rank the following strategies regarding how student understanding of physical chemistry may be improved, where 1 is the most relevant strategy and 6 is the least relevant strategy. To change the ranking, please click and drag the most relevant strategy to the top and the least relevant strategy to the bottom.
    - Students need to put forth more effort.
    - Instructors need to modify their teaching strategies.
    - More relevant examples and applications are needed.
    - Better resources, such as textbooks and visualization tools, are needed.

6. Why may it be challenging to try different teaching strategies? Please check all that apply.
    - There are no challenges.
    - Lack of time.
    - Lack of resources.
    - Lack of training.
    - Lack of interest.
    - Resistance from colleagues and/or department heads.

7. Are you willing to share a sample physical chemistry assessment? The assessment(s) will be reviewed for the content and type of questions, and will be used for research purposes only.
    - Yes
    - No

8. To gain a deeper understanding of your experiences teaching physical chemistry, are you willing to participate in a follow–up, semi–structured interview via phone, Skype, or face–to–face?
    - Yes
    - No

9. Is there anything else you would like to share regarding your experiences teaching physical chemistry?

10 What is your full name?

11. What is your email address?

12. At which college or university are you currently employed?