Topic-Specific Pedagogical Content Knowledge (TSPCK) in Redox and Electrochemistry

of Experienced Teachers

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**Stephanie O’Brien**

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in

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Topic specific pedagogical content knowledge (TSPCK) is the basis by which knowledge of subject matter of a particular topic is conveyed to students. This includes students’ prior knowledge, curricular saliency, what makes a topic easy or difficult to teach, representations, and teaching strategies. The goal of this study is to assess the pedagogical content knowledge of chemistry teachers in a professional learning community in the areas of redox and electrochemistry, as this has been regarded in previous literature as conceptually challenging for students to learn. By acquiring information regarding the PCK development of experienced chemistry teachers, the education and practice of all science teachers can be advanced. This study builds upon previous research that developed validated instruments to evaluate TSPCK. The research questions sought to determine which components of TSPCK were evidenced by the instructional design decisions teachers made, what shared patterns and trends were evident, and how TSPCK related to student learning outcomes. To answer the research questions subjects completed a background questionnaire, a TSPCK assessment, and interview tasks to elicit information about pedagogical decision making and processes that influenced student learning in their classrooms. The TSPCK exam and interview responses were coded to align with thematic constructs. To determine the effect of TSPCK on student learning gains, pre/post-assessment data on redox and electrochemistry were compared to teachers’ TSPCK. The chemistry teachers displayed varying levels of TSPCK in redox and electrochemistry, as evidenced by their knowledge of student learning obstacles, curricular saliency, and teaching methodologies. There was evidence of experienced teachers lacking in certain areas of TSPCK, such as the ability to identify student misconceptions, suggesting the need for programmatic improvements in pre-service and in-service training to address the needs of current and future chemistry teachers. While the current educational system requires teachers to complete separate exams in pedagogy and content, this research provides a rationale for changing the means by which teachers are evaluated through the completion of TSPCK assessments. In-service teacher TSPCK training is
limited yet desired by the teachers. To facilitate TSPCK development, new methods need to be explored to connect chemistry education research to practice.
Dedication

This thesis is dedicated to my family who supported my efforts with unbelievable patience. In particular, my husband Sean, for never letting me give up and, at many times, being my strength to push forward.
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Chapter 1

Introduction

1.1 Introduction and Problem Statement

In an effort to reform science education in the United States, policies and national science standards have been crafted to improve students' scientific literacy by the completion of K-12 schooling (American Association for the Advancement of Science, 1993; National Research Council [NRC], 2012). The need for reform is evidenced by benchmarking studies, such as the Program for International Student Assessment (PISA), which has repeatedly found American students’ level of scientific literacy below that of many other industrialized nations. The most recent PISA study in 2012 measured students in 22 educational systems around the world and found 18% of American students scoring below proficient levels in science (National Center for Education Statistics [NCES], 2016). This inadequate science performance has stimulated the development of new standards to improve science education and ultimately the science achievement of students across the nation. However, the most influential factor for determining student achievement is the quality of teacher training as well as the overall quality of teachers’ educational practices, thus an examination of teacher training and professional development is warranted (Darling-Hammond, 2000).

The need for developing effective teachers in the areas of science, technology, engineering, and mathematics (STEM) is critical in educating an informed citizenry (Moore, 2007). Effective teachers have mastered the structural pillars of pedagogical content knowledge (PCK), that is, they have an understanding of student misconceptions and preconceptions students bring to each specific topic within a discipline, strategies to remedy them, along with analogies, demonstrations, and the best ways of promoting student comprehension (Shulman, 1986). By studying teachers’ PCK, or the strategies and techniques effective teachers use in the classroom, information can be gathered and shared to promote pre-service training and the development of in-service teachers (Abell, 2008).

Previous studies have investigated PCK, including the ways in which it affects student learning, as well as PCK components (Magnusson, Krajcik & Borko, 1999), various PCK models (Veal & MacKinster, 1999), and how to assess PCK (Bindernagel & Eilks, 2009; Loughran, Mulhall, & Berry, 2004). Research has also examined the PCK development of novice teachers (De Jong & Van Driel, 2004; Van Driel, De Jong, & Verloop, 2002). However, there has been a lack of research showing how PCK changes over time, meaning how novice teachers develop PCK to become experts. In fact, there has been a definitive lack of experienced teachers participation in PCK research as a whole (Abell, 2008; Kind 2009).
1.2 Purpose of the Study

Research has shown that teachers have the greatest impact on student success in science, thus their training and development influences the future of science in the U.S. (Darling-Hammond, 2000; NRC, 1996). Current educational reform documents have come to define PCK as the knowledge for teaching held by expert teachers (Veal & MaKinster, 1999). Since little is known about the knowledge and beliefs teachers possess and how they are developed, there is a clear movement focused on science teacher training, both in-service and pre-service (De Jong & Van Driel, 2004; Eilks & Markic, 2011). Bucat (2005) recommended conducting case study research on expert teachers as it pertains to specific topics, such as chemical equilibrium, in order to describe master teacher "tactics," which could then be learned by pre-service teachers.

The goal of this study is to provide an understanding of the current state of pedagogical content knowledge held by chemistry teachers in a professional learning community in the areas of redox and electrochemistry. By acquiring information as it pertains to the PCK development of experienced chemistry teachers, the education and practice of all science teachers can be advanced (Boesdorfer, 2012).

1.3 Significance of the Study

This study evaluated the means by which eight experienced chemistry teachers utilized their PCK to transform redox and electrochemistry content knowledge into a comprehensible form for students. Hashweh (2005) studied teacher PCK through teacher pedagogical constructions, a series of story-based pedagogical constructions that had been created by teachers as a result of repeated planning, reflecting, and thinking about a topic. Similarly, this study explores a topic specific instance of PCK, as Hashweh suggested, that results from the planning and post-reflection of teaching the unit.

This study analyzed the instructional decisions teachers made within the topic of oxidation and reduction, or the topic specific pedagogical content knowledge (TSPCK) in redox and electrochemistry. TSPCK has been operationally defined as teachers’ combined professional knowledge of content and student learning in a particular disciplinary domain (Hill, Ball, & Schilling, 2008). Teachers provided explanations for what they identified as the big ideas and related misconceptions, as well as how they helped their students overcome misconceptions through the use of analogies, demonstrations, specific laboratories, activities, and other mechanisms for teaching the content.

Along with this information, the teachers’ rationales for their methods were evaluated to operationally define the TSPCK construct. Supplemental information such as the type of training received as well as the type of professional development acquired was noted in order to make suggestions for future generations of chemistry teachers. The results from this study will provide useful information for science teacher educators to develop more qualified teachers. By identifying weak areas of chemistry TSPCK, programmatic improvements in pre-service and in-service training may be implemented. This research provides mechanisms for changing the means by which chemistry teachers are evaluated regarding competency in teaching a specific topic within the discipline.

1.4 Research Questions

The following research questions guided the collection of data:
1. What components of TSPCK were evidenced by the instructional design decisions experienced chemistry teachers made prior to and during instruction of redox and electrochemistry?
2. What shared patterns/trends and variations were observed among experienced chemistry in TSPCK in redox and electrochemistry?
3. How was the experienced teachers’ TSPCK related to student learning of redox and electrochemistry?

1.5 Limitations

This study is limited in that the subjects of this investigation, eight experienced chemistry teachers in a professional learning community, all taught in New York State and followed the state-mandated curriculum and standards. Additionally, the teachers in the study taught populations of students who had unique characteristics; these populations may have differed from those serviced by teachers in other regions (Park & Oliver, 2008). The subjects’ TSPCK with respect to electrochemistry potentially varied from the TSPCK of other topics in the chemistry curriculum. However, teacher characteristics may be similar to others in the field of chemistry education and thus the uncovered TSPCK may be relevant and generalizable for the use of teacher educators.

The content taught in other countries even other states within the U.S. varies from the content taught in New York so their curricula may not align with the curriculum taught in this study. Although the content of the chemistry is the same, it is taught at various times within the academic calendar and to different depths of understanding in different countries. For instance, electrochemistry may not be the final or the penultimate unit taught in other countries so it might not be taught in the rushed fashion that allows for more time for high stakes test preparation.

The researcher recognizes her own bias in the study, teaching similar chemistry courses as the participants and attending many of the same professional development experiences. She consciously attempted to minimize her bias in interview questions and analysis of subjective data (Fischer, 2009). Some of the limitations were addressed by triangulating the data with multiple sources including a TSPCK exam in electrochemistry, student exam scores, survey responses, and teacher artifacts; these provided evidence of the level of PCK of individual teachers. Triangulation allowed for an analysis of TSPCK from several objective sources, thus reducing the reliance on subjective measures, such as the interview. The data were analyzed with codes and critically reviewed through multiple iterations.
Chapter 2

Literature Review

2.1 Introduction

This literature review examines the body of research that exists on pedagogical content knowledge (PCK) as it applies to the field of secondary chemistry education. The review is structured to provide a rationale for the present research. First, this review examines why chemistry as a topic is so difficult for students to understand, followed by common misconceptions in the field, particularly in redox and electrochemistry. Next, an explanation of the development and sources for the teacher knowledge base as described by Shulman will be discussed followed by the TSPCK framework. The research on chemistry PCK development that has been implemented in science teacher preparation programs and in-service programs will be discussed. Finally, an analysis of TPSCK as it relates to redox and electrochemistry will be presented along with suggestions for improving teacher competence in these areas.

2.2 Why is Chemistry So Difficult?

Researchers have identified many reasons for the perception of chemistry as a challenging subject. General chemistry introduces more terms and concepts to students than a first year foreign language class (Rowe, 1983). This, coupled with students’ inability to absorb the vast amount of information that is typically presented in the course, largely accounts for why dropout, failure and course repeater rates are above 30% at many college institutions (Rowe, 1983). Students have struggled with the relationship between the macroscopic and sub-microscopic levels, as well as conventional, inaccessible textbooks (Taber, 2002). Moreover, there has been a lack of explicit connection between chemistry and the real world, and many young people have not been stimulated to pursue the subject further (Gillespie, 1997).

Another reason so many students find chemistry difficult is the abstract nature of the concepts (Yakmaci-Guzel, 2013). Research based on the constructivist model of learning has shown that as an educator teaches, the learner makes meaning of the content through his attitude and ability, as well as retrieving background knowledge and everyday experiences, and this often results in different understandings than those of the teacher (Barke et al., 2009). Due to the complex nature of chemistry, research has reported that students have large numbers of misconceptions in nearly every chemistry topic (Gabel, 1999). One reason so many misconceptions arise may be due to the fact that chemistry textbooks are so dense in concepts, often with few examples where students can infer correct information (Taber, 2002). Besides the clarification of misconceptions, students need a firm foundation in mathematics to build a strong understanding of chemistry (Childs & Sheehan, 2009). Another difficulty in chemistry emerges from laboratory experiences, where students may be unable to link the purpose of an experiment to the content (Berry, Mulhall, Gunstone, & Loughran, 1999).
Another reason students may find chemistry difficult is the threefold representation of matter: macroscopic, sub-microscopic and symbolic. Teachers are typically more familiar with the three levels and navigate among them without much thought, sometimes leaving students confused (Johnstone, 2009). This is evidenced by the following example from Johnstone (2009) of a teacher explaining the contents of a test tube filled with a blue solution, saying, “I have here an aqueous solution of a copper salt. The blue is due to the hydration of the copper ions, written as \( \text{Cu}^{2+} \,(aq) \)” (p. 24). The teacher touched upon the macroscopic (observable), sub-microscopic (atomic level) and symbolic (representation) levels of matter inherent within chemistry. It is sometimes difficult for a high school student’s working memory to process and make meaning of all of this information into long term memory, resulting in cognitive overload which often leads to alternative frameworks (Johnstone, 2009). Similarly, Johnstone et al. (1997), in their examination of secondary science students’ ability to reason in chemistry, found students experienced difficulty when trying to solve multi-step problems.

Another difficulty students have encountered is that some everyday terms take on different meanings in chemistry. For example, dispersion forces in common language implies to spread apart, but in the world of chemistry, this refers to the forces that hold particles together (Bucat, 2004). Another example of this sort of student confusion is the belief that the melting point of a substance must be a hot (high) temperature and the freezing point for the same substance must be a cold (low) temperature (Taber, 2002). Moreover, in addition to confounding words, students often have difficulty developing a macroscopic understanding of what materials with strange sounding “chemistry names” look like. Students are not often asked questions related to chemicals with which they are unfamiliar and when questioned may be unable to envision a mental picture or establish a connection (Gabel, 1999).

One aspect of the organization of chemistry education that makes it more complicated is related to the structure of American high schools, where each discipline is taught in one year (Sheppard & Robbins, 2006). Children have been taught enormous amounts of content, with massive books they may not be able to comprehend, often leading to cognitive overload.

Students in other countries, who learn the same content over multiple years, have outperformed students in the U.S. in science as evidenced from benchmarking studies such as the Trends in International Mathematics and Science Study ([TIMSS], NCES, 2016. Johnstone (2009) suggested a total reexamination of high school chemistry because so many students have been “turned off” due to its decontextualization and the absence of links to the real world.

2.3 Chemistry Misconceptions and Their Possible Sources

Even at the highest levels of education, many students hold on to alternative conceptions. All too often, students enter the classroom with naive conceptions about chemistry, and even after direct instruction by their teachers, they sometimes leave with those same beliefs (Khourey-Bowers, 2011). Knowing the importance of student misconceptions and the barriers they present for student learning, it is important for teachers to recognize and remediate them when discussed in class (Taber, 2002; Yakmaci-Guzel, 2013). The following section will highlight some common chemistry misconceptions and possible sources.

For many students, misconceptions surrounding the particulate and kinetic nature of matter develop and hinder learning in topics such as chemical reactions, gas laws, changes in state, solutions, and equilibrium (Krajcik & Layman, 1989). Many students have a continuous view of matter and lack understanding of a sub-microscopic view; this was exemplified in a study that asked students to draw what a solution looked like under a magnifying glass. Students
constructed drawings of waves, bubbles and shiny patches, with no particle representation (Nakhleh, 1992). Additionally, while students often understood the mathematical algorithm of balancing equations, they may not have the ability to create a molecular drawing to explain on a sub-microscopic level what the reaction represented. For example, instead of drawing three hydrogen molecules as three separate entities they might be drawn as a string of six atoms connected, illustrating the failure to recognize the self-contained nature of molecular structure (Nakhleh, 1992).

Not only do students have alternative conceptions chemistry, but teachers sometimes have their own incorrect understandings that they communicate to students (Barke et al., 2009). One example of a school-made misconception is the idea that sodium chloride consists of sodium and chloride atoms bonded together in a molecule, and the chlorine atom will take an electron from the sodium to make chlorine become a negative ion and sodium a positive ion. Another example is the notion that the particles contained in mineral water are calcium chloride molecules, not ions, and the idea that ions are created through electron exchange (Barke et al., 2009). Furthermore, many students fail to understand the physical basis for bonding and come to use anthropomorphic terms such as the atom “wants” or “needs” to get a full octet (Taber, 2002).

Research has shown that misconceptions originating in primary education often result in a weak foundation for success at a higher level due to naïve understandings that cannot support new, scientifically accurate information (Nakhleh, 1992). In addition, the source of students’ original misconceptions may be a direct result of teachers’ own misconceptions. Lemma (2013) researched causes of student misconceptions and found that teachers were responsible for their students’ misconceptions in 90% of the cases examined. For example, 67% of teachers believed an atom “is like some kind of billiards object fully filled throughout by some other particles,” and 73% of their students held the same incorrect conception (Lemma, 2013, p. 43). In another instance, 17% of teachers thought “sugar is lost or disappears upon dissolving” and 26% of their students held the same misconception (Lemma, 2013, p. 50). It was when teachers did not fully explain or understand information that school-made misconceptions developed. Teacher misconceptions may be attributed to inadequate chemistry content learned at the collegiate level, since the credentials needed to become a chemistry teacher vary significantly depending on the timeframe and individual state requirements for certification.

Misconceptions are present among all levels of chemistry students, even advanced, which has led some researchers to believe they derived from ineffective teaching strategies and curricular resources (Barke et al., 2009). The benefit of studying student misconceptions is that teachers and textbook writers can address them on a regular basis (Al-Balushi, Ambusaidi, Al-Shuaiili, & Taylor, 2012). The main problem preventing this from happening is that many chemistry teachers have not been consciously aware of their students’ or their own inaccurate preconceptions and, more importantly, how to rectify them (Barke et al., 2009). It is important for teachers to be aware of misconceptions in the different subtopics of chemistry so that instructional practices can change to address the cognitive needs of students (Al-Balushi et al., 2012).

Although there has been significant research regarding student misconceptions in various chemistry topics, a disconnect exists between the science education research community and the professional community of most high school science teachers. While it seems logical that science education research data regarding student misconceptions should be used to guide instruction, it has been shown that “nine out of ten instructors are not aware of the research on student misconceptions, or do not utilize ways to counteract these misconceptions in their instruction”
(Gabel, 1999, p. 552). Gilbert, Justi, Van Driel, De Jong, and Treagust (2002) suggested pre-service and in-service instruction as a means to close the gap between research and practice by increasing chemistry teachers’ awareness of chemical education research, their use of chemical education research findings, and their involvement in chemical education research. The next section will discuss misconceptions as they relate directly to the topics of study – oxidation-reduction and electrochemistry.

2.4 Oxidation-Reduction and Electrochemistry Misconceptions

Students hold many misconceptions in the areas of oxidation, reduction and electrochemistry since they are conceptually difficult topics for students to learn (De Jong & Treagust, 2002; Garnett, Garnett, & Treagust, 1990; Nakiboglu & Tekin, 2006; Schmidt, Marohn, & Harrison, 2007). The most cited work on misconceptions in electrochemistry is a study conducted in Western Australia, where 32 students were interviewed in their 12th year of school. Students demonstrated minimal electrochemistry understanding with numerous misconceptions about electric circuits, oxidation and reduction, electrochemical cells (galvanic) and electrolytic cells (Garnett et al., 1990). Table 1 summarizes their key misconceptions in these areas. The researchers pointed to the causes of student’s inability to grasp content such as prior knowledge, alternative conventions, multiple models that reduced sophisticated concepts, and incorrect interpretation of language. The following section provides an in depth explanation of the misconceptions uncovered by Garnett et al.’s study.

Table 1

<table>
<thead>
<tr>
<th>Electric Circuits</th>
<th>Oxidation and Reduction</th>
<th>Electrochemical Cells</th>
<th>Electrolytic Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>The flow of positive charge, mainly protons, is responsible for electric current in metal conductors.</td>
<td>Oxidation and reduction reactions do not need to occur simultaneously.</td>
<td>In standard reduction potential tables the highest potential is the anode.</td>
<td>Processes at the anode and cathode are reversed.</td>
</tr>
<tr>
<td>Electricity is chemistry and physics is different because the current flows in opposite directions.</td>
<td>The oxidation state in its elemental form is the same as the charge of the monatomic ion of the element.</td>
<td>The anode is positively charged because it loses electrons and cathode is negatively charged because it gains electrons.</td>
<td></td>
</tr>
<tr>
<td>The flow of electrons constitutes current in electrolytes.</td>
<td>The addition and removal of oxygen can be used to identify a redox reaction.</td>
<td>The anode is negatively charged and because of this attracts cations and the cathode is positive and because of this attracts anions.</td>
<td></td>
</tr>
<tr>
<td>The salt bridge supplies the electrons to complete the circuit in an electrochemical cell.</td>
<td>The change in charge of a polyatomic ion can be used to identify oxidation and reduction.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrons move through the solution by being attracted by ions.</td>
<td>A polyatomic ion can be assigned an oxidation state and that equals the charge on the species.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>When an electrolyte conducts a current, electrons move onto an ion at the cathode and are carried by that ion to the anode.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Students sometimes held the misconception that electrons must complete a closed path around a cell, and consequently believed the electrons moved through the electrolyte. Students often realized that the circuit was not complete without the salt bridge but thought the salt bridge somehow supplied electrons. Other students held incorrect ideas regarding electron movement as being attracted from one ion to the next or that the electron was attached to an ion at one electrode and carried by that ion to the other electrode. The researchers noted that common everyday language may take on different meanings in chemistry so when a teacher says to a student the salt bridge “completes the circuit” students may get the idea that the salt bridge is actually supplying electrons. Additionally, students tended to think the ions actually carried the electrons from the anode to the cathode in a “piggyback approach” mechanism (Garnett et al., 1992, p.131).

In terms of oxidation states, students tended to believe the oxidation state of an element was the same as the charge of the most common ion formed by that ion (for example, saying the oxidation state of magnesium is positive two in its elemental form instead of zero). Other students thought of oxidation numbers as staying with the polyatomic ion and not relating them to elements that made up the ion so oxidation or reduction occurred because the charge of a group changed. Some students thought oxidation occurred because an oxygen atom was gained or lost. Students were taught several models and this may have caused confusion so the researchers suggested clearly communicating the limitations of models. For students who thought that oxidation means gaining an oxygen, it could be that this part of model confusion led students to believe that oxidation could occur separately from reduction (Garnett et al., 1990).

In the area of electrochemical cells, some students were not able to identify the anode and cathode using an electron potential chart. Students’ answers suggested the facts were merely memorized instead of being developed via application, for example, incorrectly identifying the anode and cathode from standard reduction potentials. Students who had difficulty in this area tended to think the anode and cathode possessed charges of their own. This caused students difficulty because some believed the anode was negatively charged and could not explain why anions drifted towards it, and those who believed the anode was positively charged could not explain why electrons moved from anode to cathode (Garnett et al., 1990).

2.5 Modifying Chemistry Instruction to Address Misconceptions

Current research has suggested students enter the classroom with knowledge or beliefs about science and that in order to teach new concepts successfully, a bridge needs to be created between students’ pre-existing understandings and new scientifically accurate ideas (Barke et al., 2009; Driver & Erickson, 1983; Taber, 2000). Since students bring alternative conceptions to the classroom, teachers should question their students at the start of a new unit to determine what they know so their planning is more effective (Taber, 2003).

One method for determining student misconceptions involves students completing a pencil and paper diagnostic multiple-choice test that offers common misconceptions as a possible answer choice (Taber, 2002). However, conceptual change methodologies, those that involve taking students’ previous conceptions into account and planning accordingly, have been the most common method (Akbas & Gencturk, 2011). An example of this would be a diagnostic tool showing students two different diagrams, one of a crystal of sodium chloride and one a solution of sodium chloride, and asking students to determine similarities and differences (Taber, 2003). Akbas and Gencturk (2011) found concept mapping to be a valuable conceptual change model for decreasing student misconceptions, however, they noted in some cases misconceptions still
remained. Another method that was found effective involved the use concept cartoons where students debated, argued about, and attempted to justify a concept (Chin & Teou, 2009). Concept cartoons contain not only cartoons of correct information but commonly held misconceptions. This difference in viewpoints enabled students to think critically to determine the correct concept and afterwards reflect on their learning (Chin & Teou, 2009).

**Electrochemistry models and strategies.** Considering the significant electrochemistry misconceptions students tend to possess, Huddle and White (2000) developed a concrete model for teaching electrochemistry. The model calls for students to first master the concept of a semi-permeable membrane prior to introducing the idea of the salt bridge, which could contain ions other than those presented in the electrolyte solution. The model contains two boxes joined by a semi-permeable membrane with polystyrene balls of different colors to represent the various atoms and ions within the system. Marbles are used to represent valence electrons and holes are made and blue sticky tack used to hold the marbles in place. Large holes are cut so that the polystyrene balls can pass in and out of the cardboard boxes. Rulers are used to separate the electrolyte solutions from the electrodes and a hosepipe is constructed to represent the wire and filled with marbles to show the flow of electrons from anode to cathode. When teachers demonstrate this model, the ions are identified, the marbles are identified as electrons, and teachers remind students the water molecules are not shown and the actual size of the atoms and ions are not the same (Huddle & White, 2000).

The model works by removing a zinc atom from the zinc electrode and removing two electrons out of the polystyrene ball and pushing them through the wire, leaving a zinc ion, which is placed in the left hand side of the box. Two electrons (marbles) are next placed into a copper ion on the right hand side of the box and the copper atom is placed at the copper electrode. Students are then directed to look at the lack of neutrality created, a zinc ion of positive charge on the left hand side has been added and a copper ion on the right hand side has been removed. To regain neutrality students can count the polystyrene balls and see that the charge is unbalanced, and to restore neutrality a zinc ion can be moved from left to right or a sulfate ion can be moved from the right to left box. Students can observe that at no point do the electrons enter the electrolyte compartment so ions are the only species moving through the semi-permeable membrane conducting charge (Huddle & White, 2000).

Like all models, this model has limitations. The actions occur as a sequence of steps rather than simultaneously. The model lacks water molecules, and the size, color, and number of molecules is not realistic. Additionally, there is no salt bridge. The benefit of the model includes the ability to show the electrons not entering the solution or moving through a salt bridge (a common misconception), the idea that the anode is decreasing in size and the cathode is increasing in size, and extensions to real life applications such as why batteries run out. This model was presented to university students in South Africa and out of the 127 students who saw the model, only one still thought that electrons could move through the salt bridge or solution, a misconception expressed by seven students in the control group who were not exposed. The model, despite the lack of water molecules, proved to be a proof of concept as an effective means to teach the sub-microscopic concepts of electrochemistry (Huddle & White, 2000).

In efforts to make the abstract nature of chemistry more accessible to students, teachers often use analogies, metaphors and models (Gabel, 1999; Taber, 2003). Analogies have strengths such as visualization of abstract concepts, comparison with something similar in the real world, and motivational function. However, textbook authors and teachers who rely on them need to be aware of their flaws including analog unfamiliarity and student’s cognitive ability to understand
them (Thiele & Treagust, 1994). Additionally, students sometimes take the device too far and transfer incorrect information, for example, the metaphor of the atom to a solar system, which may cause confusion because of the comparison of gravitational to electrostatic forces (Taber, 2002). Moreover, teachers often reduce the amount of content to reduce the complexity of chemistry, but this oversimplification leads to confusion for students who advance to higher levels of chemistry (Barke et al., 2009).

2.6 Development and Acquisition of Teacher Knowledge

**Subject matter content knowledge.** Data collected through the Praxis and other teacher exams indicated that the content knowledge of teachers is often inadequate (Ozden, 2008; Smith & Neale, 1989). Shulman (1986) described content knowledge as the information the teacher processes and organizes in her mind. Each individual teacher possesses a varying level of content knowledge. For instance, a chemistry major takes a variety of coursework to attain a bachelor’s degree, and it would be impossible to teach all of this information in the scope of a year long course to high school students. A high school chemistry teacher differs from a chemistry major in that he has knowledge of what specific concepts need to be taught in a typical yearlong course.

The Holmes Group in their first report, Tomorrow’s Future, came to the realization that subject matter knowledge, when left to the universities, did not leave students with the adequate breadth and depth of content knowledge required for teaching (Holmes Group, 1986). This was supported by data obtained from Grossman, Wilson, and Shulman (1989), who analyzed teachers’ coursework and corresponding student performance and found that strong content background did not translate into effective instruction. Rather, factors such as knowledge of what makes the content difficult to learn should be explored further. This was further evidenced by a case study of Thai pre-service teachers that revealed the following from one of the research participants regarding content knowledge:

I want to say that from all courses of the diploma in teaching programme, I can say about ninety-eight percent of my teaching I brought what I’ve learned from the methods course. I think the contents I’ve learned in other courses didn’t mean anything. I think if I didn’t learn these courses I can still teach (Faikhamta, Coll, & Roadrangka, 2009, p. 29).

This comment reveals that student teachers may value pedagogically based content courses more than strict content courses in developing chemistry teaching skills.

The disciplinary training of teachers has an impact on the information students learn in the classroom. A number of researchers examined variations in the content preparation high school teachers prior to entrance into the profession (for example, Monk, 1994). Although knowledge of content is typically learned in chemistry coursework, current research has explored the effect of embedding content knowledge into pedagogical methods courses (Etkina, 2010). Teachers enter teacher preparation programs with a wide array of content background depending on the university attended and coursework taken, which may lead to inadequate preparation for teaching the high school level curriculum (Grossman et al., 1989).

**Curriculum knowledge.** Curriculum knowledge was described by Shulman (1986) as information about programs and materials that are specific to student age and context of content, such as demonstrations, visual aides, and texts. Curricular knowledge indicates that the instructor can teach the content using multiple approaches. Geddis, Onslow, Beynon, and Oesch (1993)
found that although beginning teachers may initially find a topic simple to teach and plan appropriately, often times a deeper understanding of the curriculum, such as why particular topics are taught at all, would aid in student learning.

**Pedagogical content knowledge.** Shulman (1986) described a category of teacher knowledge called *pedagogical content knowledge* that encompasses knowledge of teaching a particular subject area in the following passage:

The most useful forms of representation of those ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations – in a word, the ways of representing and formulating the subject that make it comprehensible to others…includes an understanding of what makes the learning of a topic easy or difficult: the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning of those frequently taught topics and lessons (Shulman, 1986, p. 9).

In a later publication, Shulman (1987) expanded on the three knowledge bases previously discussed, admitting that he had previously omitted some, and claimed the teacher’s knowledge base is comprised of the following seven components: 1) content knowledge, 2) general pedagogical knowledge, 3) curriculum knowledge, 4) knowledge of learners and their characteristics, 5) knowledge of educational contexts and knowledge of educations goals, 6) beliefs, and 7) theory of education (Shulman, 1987). Grossman (1990) subsequently identified the four categories of teacher knowledge as general pedagogical knowledge, subject matter knowledge, pedagogical content knowledge, and contextual knowledge. Although all previous research may not agree on all aspects of a teachers’ knowledge base, most include PCK as a component. The next section will discuss PCK in more detail, beginning with the history of how it has been operationalized and expanding upon its application to disciplinary subdomains. The measurement of PCK and its inclusion in teacher education programs will also be discussed.

### 2.7 History of PCK

PCK has been described by Shulman as “that special amalgam of content and pedagogy that is uniquely the province of teachers, their own special form of professional understanding” (Shulman, 1987, p. 8). Geddis et al. (1993) described PCK as the transformation of subject knowledge into the form students find accessible. Baxter and Lederman adapted PCK as “what a teacher does, and the reasons for the teacher’s actions” (Baxter & Lederman 1999, p. 158). Van Driel, Verloop, and De Vos (1998) refined the definition as:

…integrated knowledge which represents the teachers’ accumulated wisdom with respect to their teaching practice. As craft knowledge guides the teachers’ actions in practice, it encompasses teachers’ knowledge and beliefs with respect to various aspects such as pedagogy, students, subject matter, and the curriculum (Van Driel et al., 1998, p. 674).

Although some variations in the definition of PCK exist, researchers agree on two aspects of what composes PCK: knowledge of students learning difficulties and preconceptions, and knowledge of subject matter representation (Van Driel et al., 1998).

Magnusson et al. (1999) conceptualized PCK for science teaching to include the following: orientation to teach science, knowledge of science curricula, knowledge of assessment of
scientific literacy, knowledge of instructional strategies, and knowledge of students’ understanding of science. Adding to this structure, Park and Oliver (2008) summarized the components of PCK with six integral and interrelated parts: 1) orientation to teaching science, 2) knowledge of assessment of science learning, 3) teacher efficacy, 4) knowledge of students’ understanding in science, 5) knowledge of teaching science, and 6) knowledge of instructional strategies for teaching science. While increasing one aspect may also lead to the increase in another, it is the integration of all facets that forms the construct of PCK.

The concept of PCK has been explored in other academic subjects such as mathematics. Ball, Thames, and Phelps (2008) used the ideas set forth by Shulman (1986) and identified similarities in mathematics, such as finding that teachers who lacked content knowledge in their subject area also lacked PCK. Secondly, in agreement with science PCK research provided by Gess-Newsome (1999), a teacher’s ability to know content is not enough, rather, he needs to know how to make the subject matter useful and use understandable representations and forms. However, Ball et al. (2008) noted that it would be interesting to determine whether there are certain aspects of teachers’ knowledge that affect student achievement more than others, but there is an absence of literature to describe this. If more studies examined teachers’ specialized content knowledge, then pre-service programs could be structured to achieve improved student success.

2.8 Development of PCK

Shulman (1987) discussed the sources by which PCK is acquired and developed. The first way to learn PCK is through instruction in the content discipline that an individual experiences in school as a child. PCK is also learned through educational materials such as the course scope, sequence, and testing materials. In teacher preparation, PCK is developed in methods coursework and through the practice of teaching. Grossman (1990) also discussed PCK obtained via four sources that included: apprenticeship of observation, subject matter knowledge, teacher education, and classroom experience. Consequently, teachers develop their PCK by reflecting on their past school experiences as a child, incorporating theory and beliefs developed during pedagogical methods coursework specific to the discipline, and forming strategies and representations of the subject matter.

2.9 Topic Specific PCK

Effective teachers need to develop knowledge with respect to all topics they teach (Magnusson et al., 1999), and science education researchers should explore specific aspects of teacher content knowledge (Abell, 2008). The idea of PCK within a topic has been explored in a study by Veal and MacKinster (1999). They proposed general PCK taxonomy as knowledge of a discipline such as science, which can be divided into domain specific PCK such as chemistry or physics, which can be further subdivided into topic specific PCK such as oxidation, stoichiometry, solubility, etc. The construct of topic specific PCK (TSPCK) has been further supported by Loughran, Berry and Mulhall (2006) and, more recently, Mavhunga and Rollick (2013) have come to clearly define its components. TSPCK provides the needed knowledge for subject matter knowledge transformation in a particular topic, which includes students’ prior knowledge, curricular saliency, what makes a topic easy or difficult to teach, representations including analogies, and teaching strategies.
Mavhunga (2012) took the work done in the field of mathematics by Ball et al. (2008) to develop a model that described TSPCK or the teacher knowledge of a particular topic subject matter transformation. Figure 1 shows this model, which included: a) learners’ prior knowledge b) curricular saliency c) what makes a topic easy or difficult to teach d) representation including analogies and e) conceptual teaching strategies (Mavhunga, 2012). These components were supported by other researchers in the field such as Geddis and Wood (1997), who examined the PCK in one particular topic. Learners’ prior knowledge includes the misconceptions and alternate conceptions students have about a particular topic. Curricular saliency means the teacher knows what should be taught how much time and in what order the topic should be taught. What makes the topic easy or difficult means the teacher is able to identify big ideas and the pieces that student struggle to understand along with methodologies and awareness when teaching the topic. Representations include analogies, simulations, models or illustrations that vary the means by which students are exposed to the topic (Mavhunga & Rollnick, 2011).

![Figure 1. Topic specific PCK model (Mavhunga, 2012).](image)

### 2.10 Measuring PCK

It is difficult to assess the PCK of a teacher due to its many components, as well as consideration of the other knowledge bases that affect PCK (Friedrichsen & Dana, 2003). Following the same line of reasoning, Baxter and Lederman (1999) established the difficulty of assessing PCK due to its nature as an internal construct, one that cannot be identified in a single lesson since that would not dictate all the representations a teacher utilizes. Also, the lesson context may not reveal why a teacher chose to use a certain method or approach. Additionally, most techniques have been time consuming to analyze and it is difficult to determine the cognitive processes of the teacher, as some components of PCK are unconsciously determined (Baxter & Lederman, 1999). Moreover, what Baxter and Lederman (1999) called “convergent
and inferential” techniques, such as Likert-scales that were self-reported and multiple-choice, may not have been the most appropriate instruments to measure PCK. Consequently, researchers have utilized multiple methods of assessment such as observations, researcher inference, interviews, as well as the tools presented in the following section. This section on PCK assessment strategies does not include every technique, just some that are representative.

**Card sorting.** Card sorting was designed with the intention of eliciting information from teachers about their goals for student motivation during a science lesson (Friedrichsen & Dana, 2003). While there are variations in the ways in which card sorting can be used, in past research it has served as a valuable means to determine the goals and philosophies of pre-service science teachers. Teacher candidates were asked to place a list of science teaching scenarios (cards) into three piles: agree, disagree, or unsure. This was followed by a variety of approaches such as peer interview, journal logging or reflection papers that described why cards were selected, how they supported the candidates’ goals and purposes, why certain cards did not support their teaching philosophy, and, finally, a comparison of cards to show where teaching philosophies aligned with their choices. Often times the researchers found that information obtained via interviews was more valuable than the sort itself in providing insights about teachers’ science orientations. While the researchers agreed there were limitations to card sorting, such as subjective interview choices and the varying perspectives of subjects, they found it to be to be a useful technique to assist beginning teachers in sharing their goals and beliefs regarding science teaching (Friedrichsen & Dana, 2003).

Card sorting is an alternate technique that does not provide the topics to the participant, thus allowing for more variation in the format of the final product (Baxter & Lederman, 1999). Concept maps, card sorts, and pictorial representations have been used by researchers to gain understandings regarding a teachers knowledge of terms and relationships within and between various topics. Some negative aspects of this work include the lack of long term studies showing their effects as well as researchers’ difficulties inferring the stories told by the diagrams (Baxter & Lederman, 1999).

**Roadmaps.** Research done by Bindernagel and Eilks (2009) created a means to evaluate the PCK of 28 experienced German chemistry teachers through examination of the sequence in which they taught the particulate nature of matter and used models. Information was obtained via interviews conducted by 56 student teachers in their fourth year of study accompanied by an assistant from the university. This fostered a non-threatening environment, where experienced teachers offered insights on their PCK concerning the particulate nature of matter. The interviews were 45 minutes in length. The student teachers were given a guide including questions about the teachers’ use of models, specific learning strategies, learning difficulties, as well as textbooks used when introducing the particulate nature of matter. The teachers interviewed were randomly selected, mostly between the ages of 40 and 60, 25 of whom had been teaching chemistry for more than five years, and 24 who had taught at least five hours of chemistry a week. The student teachers put together a ten-minute presentation from the interviews to share with their peers. Subsequently, there was a group work component where the presentations were compared with literature regarding student preconceptions and learning difficulties (Bindernagel & Eilks, 2009).

Roadmaps were created to portray the paths the teachers followed with lines indicating the number of teachers following that path and nodes with the description of the model used. The
experienced teachers discussed three levels of models: discrete particles, atoms with structure, and covalent bonding and structure. Most teachers favored a structure of teaching that focused on the history of science and used between three to seven models, although the more models the teachers used, the more they blended the models together. Some teachers did not teach the models in historical order and some formed hybrid models that did not actually exist. Many were not able to describe learning difficulties associated with the use of these models (Bindernagel & Eilks, 2009).

One implication from the study was that roadmaps explicitly revealed the PCK of the teachers studied. An evaluation of the roadmap resulted in numerous conversations about the best ways to teach this particular topic and was an effective tool for pre-service teachers. Finally, the authors pointed out that additional case studies were being performed to develop roadmaps so chemistry teachers might explicitly relate the decisions they make to their rationales (Bindernagel & Eilks, 2009).

**CoRe and PaP-eRs.** An alternate strategy used by Loughran et al. (2004) measured the level of PCK of more than 50 teachers who taught general science as well as upper level science in Australian high schools through the use of Content Representations (CoRe) and Pedagogical and Professional experience Repertoires (PaP-eRs). The data came from three phases of research, the first being individual interviews with science teachers where teachers discussed information regarding teaching procedures and events. The next part of the research involved teacher observations and the assessment of student understanding, and a final component of the research involved small groups of teachers developing content representations. The CoRe revealed the teachers’ thoughts about the big ideas of the content and why they were important. Two other areas in the CoRe were students’ misconceptions and how they affected their ability to learn. The CoRe was verified by another group of teachers who rephrased some of the information for clarity. This was further examined by an additional small group of teachers to ensure it was understandable. Results showed that the methodology of using CoRe and PaPers to represent PCK provided a valid and concrete but time-consuming method (Loughran et al., 2004).

**Laboratory assessment.** There has been research specifically focused on the laboratory setting at the undergraduate level which assessed PChK, or chemistry PCK development among graduate teaching assistants (GTAs) in undergraduate chemistry labs (Bond-Robinson, 2005). Two instruments were used to measure PChK, one that the instructor used and one that the undergraduate TAs used. Five categories were established - $\text{Ch}_0$, $\text{Ch}_1$, $\text{Ch}_2$, $\text{Ch}_3$, and $\text{Ch}_4$ – depending on the amount of chemistry discipline-related PCK implemented by the GTAs in their instruction. $\text{Ch}_0$ was GTA knowledge that was unrelated to chemical concepts. $\text{Ch}_1$ required the GTAs to give procedural guidance and advice. $\text{Ch}_2$ required the GTAs to use analogies, models or representations to link the laboratory experiments to the abstract concepts sub-microscopic level or atoms and molecules, which would require preparation to make these connections possible with transformational explanations. $\text{Ch}_3$ called for GTAs to use direct and indirect questioning with the UGs to promote discussion about how and why to proceed in the experiment. This study showed that $\text{Ch}_4$ was the most difficult to attain, followed by the previous categories sequentially. $\text{Ch}_1$ was reported to occur mainly at the macroscopic level. The amount of $\text{Ch}_2$ and $\text{Ch}_3$ was less used due to the lack of constructivist teaching styles modeled when the GTAs were students, and, secondly, the nature of the chemistry topics on the sub-microscopic level.
Many of the behaviors exhibited by the GTAs were similar to those of pre-service science teachers (Bond-Robinson, 2005). This model provides a worthwhile training strategy that might be implemented into teacher preparation programs.

**TSPCK instrument.** According to Tepner and Dollny (2011), content knowledge and pedagogical content knowledge can be measured using a large-scale test instrument. In their study, 126 teachers were asked to complete a paper and pencil questionnaire to assess both content knowledge and PCK, which took 45 minutes to complete. Common topics were tested, including atomic structure, the periodic table, chemical bonding, and acid-base chemistry. The PCK instrument contained 25 multiple-choice items and the PCK instrument contained 19 items. The results of this study showed a moderate correlation between teachers’ content knowledge and their PCK regarding misconceptions in the same topic, suggesting content knowledge is necessary to develop quality PCK. The study is valuable in that it showed the use of a large-scale tool that can be used to assess content knowledge and PCK.

Mavhunga and Rollnick (2013) developed and evaluated a tool for measuring TSPCK in chemical equilibrium. Specifically, the instrument examined the teachers’ PCK as it related five components: 1) learners’ prior knowledge including misconceptions and alternate conceptions, 2) what makes a topic easy or difficult to teach, 3) curricular saliency, 4) representations including examples, simulations and analogies, and 5) teaching strategies. The questions in the TSPCK instrument were designed for the teachers to provide explanations for their chosen responses. The researchers first scored the TSPCK using the rubric and then two peer reviewers, one physical science teacher and one doctoral student, also rated the exams and differences were resolved via conversations to obtain 85% agreement. The results showed that teachers had the most difficulty with conceptual teaching strategies and were most successful with assessing prior knowledge. The second highest scoring area of the TSPCK test was what makes the topic difficult to teach followed by curricular saliency and then representations (Mavhunga & Rollick, 2013).

Rollnick and Mavhunga (2014) reported the value of the TSPCK tool to evaluate pre-service teachers’ conceptual understanding. The TSPCK test was also designed for the topic of oxidation-reduction and electrochemistry and given to a sample of 12 teachers who volunteered to participate, varying in experience from five to 20 years. The TSPCK framework included learners’ prior knowledge, curricular saliency, what makes the topic difficult to learn, and representations and conceptual teaching strategies. A rubric was used to determine the TSPCK based on the exam. The teachers were given a content test in addition to the TSPCK test and it was found that although many pre-service teachers had strong content knowledge as measured by the content exam, their TSPCK was weak. The researchers suggested using the instrument in other countries to develop a “baseline” level of teacher knowledge (Rollnick & Mayhunga, 2014).

**Summary.** Most scholars have utilized mixed methodologies to determine the level of PCK of the research subjects, including strategies such as interviews, concept mapping and video-prompted recall, from which data may be triangulated to develop a PCK snapshot (Baxter & Lederman, 1999). However, this type of approach is time consuming and not always able to be replicated. PCK is difficult to assess due to its complexity and abstract nature, however, current methodologies such as paper and pencil examinations, concept maps, interviews, visual representations, and multi-method approaches have demonstrated some value in measuring PCK (Baxter & Lederman, 1999). The information obtained through this research may be valuable for
improving pre-service teacher training, in-service professional development, and teacher evaluation.

2.11 PCK Development in Teacher Preparation Programs

Universities are entrusted with the preparation of teachers by providing the tools necessary to ensure the success of their candidates. In order to accomplish this, science education programs are charged with graduating teachers who are able to make science understandable and memorable (Nezvalova, 2011). To build solid pre-service programs, knowledge of what teachers know and believe needs to be incorporated (Eilks & Markic, 2011). Conventionally, teacher preparation programs in science are structured with the candidate first completing coursework in their area of certification, followed by coursework in pedagogy. However, research has suggested that linking the two components into one domain would be far more effective (Etkina, 2010). Other research has examined the number of courses completed by pre-service teachers and its relationship with the transmission of knowledge to students (Monk, 1994). Subject specific methods coursework has been more influential in student learning (Gess-Newsome et al., 2010).

Monk (1994) evaluated data obtained via the Longitudinal Survey of American Youth (Miller & Kimmel, 2010), which examined the students’ science knowledge upon entrance to high school and learning differences related to teacher preparation, measured by pre- and post-examinations. One notable finding from his study was that teachers who completed more graduate coursework in their chemistry or physics content areas tended to have students who performed at a lower level in their respective classes. In fact, teacher pedagogy coursework was shown to have a greater impact on student success than additional content coursework. One implication of this study was that the traditional methodology of teacher preparation including four years of content work at the undergraduate level, followed by an additional year of pedagogical study, may not be the most cost effective or sound process to develop high quality teachers. Ball et al. (2008) suggested that teacher preparation programs are often too focused on academic content and fail to make it relevant. The following section will provide chemistry specific examples of interventions at the pre-service level to aid in PCK development.

**TSPCK: Particulate nature of matter.** One example of a study focused on improving pre-service teachers’ TSPCK is that of De Jong and Van Driel (2004), who conducted research on eight student teachers in a graduate program in secondary education. They looked at the development of pre-service teachers’ PCK in the area of the particulate nature of matter by examining lesson plans, classroom teaching, and reflections, all of which focused on the “learning from teaching” as opposed to the “learning of teaching” (De Jong & Van Driel, 2004, p. 477). Participants chose a topic from the curriculum and focused on the relationship among macroscopic, sub-microscopic, and symbolic representations. Research data were obtained by interviewing the student teacher candidates before and after each lesson. The authors coded the transcripts and created categories of student learning difficulties as well as categories of teaching difficulties. To utilize researcher triangulation, both authors individually determined common student difficulties. The researchers also employed the constant comparative method, whereby the analyses of student teacher interviews were compared with classroom dialogue transcripts and textbooks to determine the source of the student teachers’ word choice.

At the conclusion of the study, it was revealed that all participants reported student learning difficulties and were able to discuss these problems with more detail than they had prior to
giving their lessons. The main difficulty for the student teachers was a fast “zigzag” between the macroscopic and sub-microscopic, a natural tendency to use the sub-microscopic most often, and a mixing of the macroscopic and sub-microscopic meaning of topics. The research showed that although student teachers were initially unaware of any learning difficulties arising from the textbooks, in particular formulas and reactions related to the macroscopic and sub-microscopic, following the lessons they were more aware of their problematic reliance on textbooks (De Jong & Van Driel, 2004).

De Jong and Van Driel’s study has important implications for PCK development. Student teaching develops knowledge of student learning difficulties. While the macroscopic, sub-microscopic and symbolic representations start to become second nature after years of schooling, the information may be confusing to the students who are initially introduced to the material. The research suggested using literature to reflect upon student preconceptions, strategies, and learning difficulties (De Jong & Van Driel, 2004). Further studies could investigate the benefit of using chemistry education research regarding student learning difficulties to develop pre-service teachers’ TSPCK.

Pre-service PCK coursework. Research conducted by Faikhamta et al. (2009) examined the development of a PCK-based methods course and its impact on teaching. The participants in this study were four 23-year old, pre-service chemistry teachers in the Graduate Diploma Program at a university in Thailand, who were chemistry majors taking a chemistry PCK class as a pre-service requirement followed by a second semester of student teaching. Data were collected via observations, semi-structured interviews, surveys on content and student beliefs, as well as other documents. They were analyzed through categorical aggregation to determine trends. The results indicated that all pre-service teachers initially struggled with knowledge of student alternate conceptions but were able to improve through their experiences in the schools. Another effective aspect of the program was the reflective component where students wrote weekly journals, reflected on their teaching practice from video tapes, focused on the weaknesses of their own teaching, and commented on their peers’ alternate strategies (Faikhamta et al., 2009).

By the end of the pre-service teachers’ second microteaching observation, prior to field experiences, they had all incorporated PCK components into planning, learning outcomes and sequence, and media and assessment techniques. This was a tremendous improvement from their first lesson plans where components of the lesson were not necessarily related to the next. However, one limitation of the study was that it was difficult to discern whether their success was due to the specific nature of the chemistry PCK program or simply due to the nature of the time spent learning in the classroom (Faikhamta et al., 2009).

Finally, the case study showed that students’ implementation of PCK was inconsistent in their field experiences. Although the candidates planned to execute lessons grounded in constructivist views, the candidates themselves exhibited weak strategies such as excessive lecturing and asking questions that were too difficult. Future research should examine modalities for assisting pre-service teachers in implementing PCK into their teaching through seminars, workshops, conferences, and action research (Faikhamta et al., 2009).

Rutgers University offers an example of a science teacher preparation program that focused on PCK in the development of physics teachers (Etkina, 2010). Etkina provided a physics model that can be duplicated in other universities and disciplines to provide the opportunity for significant PCK development during pre-service training. Students in the teacher preparation program at Rutgers completed six courses in PCK that incorporated physics content, how to plan
and best place the content in the curriculum, and how to engage students in learning the content. The courses prepared the pre-service teachers in teaching methodologies and practices they would be expected to utilize in future placements. Some features of the program included teacher modeling constructivist style lessons, collaborative planning and microteaching, and experiences in observing, teaching and reflecting on the practice of teaching (Etkina, 2010). While this program was for prospective physics educators, aspects of this model could be used to train chemistry teachers.

**Workshops to assist in PCK development.** Van Driel et al. (2002) implemented a workshop as an intervention to assist in the development of chemistry PCK. They studied 12 pre-service teachers of chemistry, all of whom had completed a master’s degree in chemistry and had little or no teaching experience. The qualitative methodology utilized data collected at various points during the first semester of the program. Data included a baseline assessment of pre-service teachers’ knowledge of the macroscopic and sub-microscopic domains of chemistry. This assessment was administered after a transcription of audiotaped workshop conversations was given to both groups about the macro-micro domain of chemistry. Semi-structured interviews were conducted at the end of the first semester to discuss reflections; interviews were also conducted with the mentors of these pre-service teachers to discuss their views about the pre-service teachers’ development. PCK questionnaires were administered to the student teachers (Van Driel et al., 2002).

The data were analyzed by creating categories for the pre-service teachers’ PCK. The pre-service teachers all developed their PCK in the macroscopic and sub-microscopic domains and they particularly improved their identification of student learning difficulties. Additionally, they realized they navigated too quickly between the domains, so they needed to state explicitly when they were doing so. Additionally, pre-service teachers reported that the classroom experience had the greatest impact on their PCK development. The workshops also helped develop content knowledge and the Harrison and Treagust study (1996) was useful in identifying the learning difficulties students faced as well as strategies to mitigate those difficulties. Finally, the intervention of mentors greatly increased the students’ PCK (Van Driel et al., 2002).

The authors suggested that pre-service teachers engage in action-research and field-based questioning to explore students’ conceptions in the macroscopic and sub-microscopic domains. This could involve questioning students and examining test responses. Another implication was that the workshops could serve as an optimal opportunity to discuss educational research literature. Research should explore the role of mentors in pre-service programs and the benefits of developing pre-service teachers’ PCK. Additionally, research should investigate how pre-service education programs might focus on subject matter knowledge in addition to pedagogy and field experiences since this study revealed inadequacies in subject matter knowledge (Van Driel et al., 2002).

### 2.12 The Redox and Electrochemistry Knowledge of Pre-Service Teachers

Ahtee, Asunta, and Palm (2002) studied student teachers’ conceptions of electrolysis to determine what content and pedagogical difficulties they experienced as they taught the topic. Eight student teachers were involved in the study, all of whom were chemistry majors and had completed the chemistry content and pedagogy requirements and had entered the subject specific pedagogy preparation of their program. The student teachers in the study were asked to develop a
lesson plan for 14- to 15-year old students on the topic of electrochemistry that began with the use of a key demonstration. The student teachers were given an hour and a half to draw up a lesson plan without the use of a textbook to guide them. Subsequently, the student teachers filled out a questionnaire and completed a half-hour interview. The responses provided via interview were compared with the written lesson plans and questionnaire and placed into one of four categories: 1) knowledge of the topic, 2) reasons for selecting the key demonstration, 3) proposed teaching sequence and pedagogical content knowledge, and 4) expected difficulties and concerns (Ahtee et al., 2002).

The results of the study showed that only two of the eight teachers had knowledge of the topic; many just presented what happens in an electrolytic cell without explaining the scientific rationale for the process. The results were consistent with that of Garnett and Treagust (1992), who showed student teachers had trouble with the sign of the anode and cathode as well as what ions would be present in the solution. When asked why they chose the key demonstration, teachers responded in one of two ways. First, it was concrete and had practical value such as motivating student interest. Secondly, the demonstration was one they remembered from their coursework or teaching training. None responded that the demonstration would uncover misconceptions or learning difficulties in the topic, or that it would help students understand electrolysis. Moreover, none of the students were asked to make predictions about what would happen in the demonstrations (Ahtee et al., 2002).

As far as the proposed teaching sequence and PCK, the student teachers were unsure how to incorporate previously learned content and connect it to electrolysis, and they considered electrolysis one isolated example of redox reactions. Only four of the eight students teachers thought students would understand electrolysis after they taught it. The student teachers expected difficulties and concerns focused around insufficient content knowledge, their ability to teach the content well, and their inability to time appropriately and guide discussions (Ahtee et al., 2002).

Ozkaya (2002) studied 92 pre-service chemistry teachers in Marmara University in Istanbul, Turkey, who were in their final year of study and had spent three and a half months studying electrochemistry in the classroom and laboratory. Fifteen students were interviewed using an adapted Garnett and Treagust (1992) protocol, followed by a 27-item multiple-choice examination consisting of statements designed to uncover misconceptions. The volunteer participants were selected based on their scores in the electrochemistry course at the university. Five participants were lower performers, five upper, and five middle range students. This study showed how interview data could be used to construct assertion-reason-type questions that were then used to determine misconceptions that had not been previously reported in the literature (Ozkaya, 2002).

The results uncovered not only misconceptions via the assertion piece of the exam but the reasons they thought the misconceptions were true. The researcher identified assertions and reasons that had not been previously reported in the literature prior to this study. One naïve idea was that half-cell potentials could be used to predict the spontaneity of the half-cell reactions because some half-cell potentials are positive while the others are negative in value. Another misconception was the value of zero for the standard potential of the hydrogen was somehow based on hydrogen’s placement in the middle of the activity series for metals. Additionally, student teachers thought that in galvanic cells, the identity of the anode and cathode depended upon the physical placement of the half-cells because IUPAC convention requires the placing of the cathode on the right and the anode on the left in the cell notation (Ozkaya, 2002).
The study concluded that misconceptions in electrochemistry were evident across various countries. The consistency in identified misconceptions suggested that the teaching of electrochemistry was often not done properly, either due to poorly constructed learning experiences or textbooks with faulty or misleading content. The researcher indicated that grades in collegiate level electrochemistry courses tend to be high, likely due to students’ ability to master algorithms and solve the quantitative calculations necessary to achieve at this level, however, the conceptual understanding of the topic was evidently lacking in this case (Ozkaya, 2002). The limited PCK of these pre-service teachers is of concern because of the difficulty in addressing student misconceptions when their own misconceptions limit their chemistry understanding.

Problems with electrochemistry in textbooks. The idea of misleading or erroneous textbooks in the area of redox and electrochemistry was reported by Sanger and Greenbowe (1999), who reviewed ten chemistry textbooks and found many printed misconceptions that had been cited in literature. For example, due to the way electrochemical cells are typically drawn in textbooks, students tend to believe the physical placements of the half-cells indicate the identity of the anode and cathode. Additionally, students sometimes believe electrons can flow though the salt bridge and electrolyte solution. Students are also confused about how cation movement can be involved electrical current, and how electrodes with large net positive or negative charges could be responsible for ion and electron flow. Finally, they found that one cannot predict the products of electrolysis using standard reduction potentials. Because of their findings, they suggested that teachers and textbook writers should not always draw the anode on the left and cathode on the right or only discuss anion movement. Moreover, they suggested using the difference method to calculate cell potential instead of the additive method, and to not use simple electrostatic arguments to show where ions and electrons move within the cell. Finally, they suggested that more than one possible oxidation and reduction half-reactions should be considered if students are tying to predict the products of electrolysis (Sanger & Greenbowe, 1999). These findings were consistent with those reported by Garnett & Treagust (2002). Table 2 below summarizes misconceptions identified in the combined work of Garnett and Treagust (2002) and Sanger and Greenbowe (1999).
Table 2
Common Student Misconceptions in Electrochemistry

GALVANIC CELLS

1. In an ordered table of reduction potentials, the species with the most positive \( E_0 \) value is the anode.
2. Standard reduction potentials list metals by decreasing reactivity.
3. The identity of the anode and cathode depends on the physical placement of the half-cells.
4. Anodes, like anions, are always negatively charged; cathodes, like cations are always positively charged.
5. The fact that the \( E^\circ \) for \( H_2(1 \text{ atm})/H^+(1 \text{ M}) \) is zero is somehow based on the chemistry of \( H^+ \) and
6. There is no need for a standard half cell.
7. Half-cell potentials are absolute in nature and can be used to predict the spontaneity of the half-cells.
8. Electrons enter the solution from the cathode, travel through the solutions and the salt bridge, and emerge at the anode to complete the circuit.
9. Anions in the salt bridge and the electrolyte transfer electrons from the cathode to the anode.
10. Cations in the salt bridge and the electrolyte accept electrons and transfer them from the cathode to the anode.
11. Cations and anions move until their concentrations are uniform.
12. Electrons can flow through aqueous solutions without assistance from the ions.
13. Only negatively charged ions constitute a flow of current in the electrolyte and the salt bridge.
14. The anode is negatively charged and releases electrons; the cathode is positively charged and attracts electrons.
15. The anode is positively charged because it has lost electrons; the cathode is negatively charged because it has gained electrons.
16. Cell potentials are derived by adding individual reduction potentials.
17. Half-cell potentials are not intensive properties.

ELECTROLYTIC CELLS

1. In electrolytic cells, the direction of the applied voltage has no effect on the reaction or the site of the anode and cathode.
2. No reaction will occur if inert electrodes are used.
3. In electrolytic cells, oxidation now occurs at the cathode and reduction occurs at the anode.
4. In electrolytic cells with identical electrodes connected to the battery, the same reactions will occur at both electrodes.
5. In electrolytic cells, water is unreactive toward oxidation and reduction.
6. When predicting an electrolytic reaction, the half-cell reactions are reversed before combining them.
7. The calculated cell potentials in electrolytic cells can be positive.
8. There is no relationship between the calculated cell potential and the magnitude of the applied voltage.
9. Inert electrodes can be oxidized or reduced.
10. When two or more oxidation or reduction half-reactions are possible, there is no way to determine which reaction will occur.
11. Electrolytic cells can force nonspontaneous reactions that do not involve electron transfer to happen.

CONCENTRATION CELLS

1. The direction of electron flow in concentration cells is not dependent on the concentration of the ions.
2. The products produced in the indirect reaction of electrochemical cells are different from those produced in the direct reaction of the starting materials.
3. The cell potential in concentration cells is not dependent on the relative concentration of the ions.
4. Because there is no net reaction in concentration cells, the reaction quotient cannot be calculated.

Summary. The research above highlights the benefit of interventions to help pre-service chemistry teachers develop PCK. Although PCK develops over time, this review has highlighted some examples of ways to improve teachers’ pedagogical skills. The research also provides guidance for understanding students’ misconceptions and strategies for scientifically accurate
comprehension. In light of this, this present study identifies TSPCK in electrochemistry, which has the potential to enrich the knowledge of prospective teachers in pre-service programs.

In summary, the structure of teacher preparation programs need to be amended to offer PCK discipline specific courses. These courses provide techniques for uncovering student misconceptions and ways to change the alternate conceptions of students (Schneider & Plasman, 2011). Moreover, since PCK develops over time, courses, workshops and professional development opportunities rich in content specific PCK need to be provided to help teachers become better educators. If teachers are better prepared with strategies to address the abstract nature of chemistry and combat student misconceptions through conceptual change models, perhaps students will not leave high school with the impression that chemistry is a “killer course” and instead be enthusiastic about embracing the subject.

2.13 Why Should PCK Development be Promoted for In-Service Chemistry Teachers?

In-service chemistry teachers and pedagogical content knowledge. To become a better educator, is imperative that teachers engage in professional development opportunities to expand their knowledge base, build their understanding and abilities, and reflect on their individual science PCK, learning, and pedagogy (NRC, 1996). Since only a fraction of PCK develops during pre-service education, in-service opportunities provide a means for teachers to develop their PCK (Mangusson et al., 1999). Hume and Berry (2011) provided evidence for the use of CoRe designs as a means to develop pre-service teachers’ PCK in a variety of disciplinary topics. One area investigated was redox and electrochemistry, and the researchers showed that student teachers need more PCK development since students found the examination of their PCK to be an informative and reflective process. Furthermore, since teachers are often responsible for creating student misconceptions due to their own weak understandings, it is important to provide them with the tools necessary to deepen their knowledge of chemistry and its subtopics (Bucat, 2004; Lemma, 2013).

Professional development. Khourey-Bowers and Fenk (2009) researched the relationship between chemistry constructivist professional development and teacher growth in content knowledge, particularly in the use of scientific models in instruction, PCK, and self-efficacy. The study explored volunteer in-service teachers of various backgrounds, some of whom were elementary certified and others with middle and secondary certification. The study was conducted with two cohorts through a grant funded, five-credit professional development course, which was given over a six-month span, totaling 11 sessions. A team comprised of a university science teacher, a chemistry professor and two experienced chemistry teachers led the professional development. Pre- and post-tests were administered to assess content knowledge and PCK through an examination focused on improving representational thinking. PCK was examined through a lens of how the teachers elicited alternative conceptions, provided linking activities to assist student thinking about science concepts, and used analogies effectively. The study showed the professional development led to teacher lesson narratives that showed enhanced PCK. The scoring rubric was not provided nor was an explanation of how the levels of representation were developed (Khourey-Bowers & Fenk, 2009).

Aydin & Boz (2013) studied the PCK of two experienced chemistry teachers in two different topics – electrochemical cells and nuclear chemistry. Data were collected from observations, card-sorting activities, Content Representation (CoRe), and interviews. Results showed that the
methodologies in which the content was taught remained consistent between the two topics. However, the sub-components of PCK such as knowledge of curriculum, knowledge of assessment, and knowledge of learners varied from one topic to another. This study showed how the use of a CoRe, a methodology typically done in a group setting, could be utilized to individually assess TSPCK (Aydin & Boz, 2013).

**Web-based courses.** One approach that has facilitated the development of chemistry teachers’ PCK and TSPCK is the use of web-based online courses. One model funded by the National Science Foundation provided high school chemistry teachers with courses on specific topics in chemistry to strengthen their PCK in a particular area of their choosing. While limitations of a web-based approach include a pace set by the instructor and absolute participant completion, the structure was flexible for teachers and provided a means to enhance TSPCK and strengthen conceptual understanding (Brooks et al., 2007).

**Workshops.** Another approach to facilitating topical PCK in chemistry was a workshop model, conducted by Van Driel et al. (1998) in an effort to help teachers recognize specific preconceptions and learning difficulties in the area of chemical equilibrium. Teachers also learned how to facilitate interventions to address these naïve ideas. Instead of just giving teachers a checklist of the top strategies for teaching the topic, the workshop was taught using a constructivist style where teachers first discussed their own conceptions of chemical equilibrium and responded to textbook and authentic student responses. This was followed by an experimental course. The results of this study showed most of the participants considered chemical equilibrium to be an area of difficulty for students yet they were unfamiliar with the literature explaining student conceptions of the topic. Moreover, many of the teachers lacked a theoretical understanding of the dynamic nature of chemical equilibrium and failed to promote scientifically accurate student understandings. Most teachers had created their own system of anthropomorphic analogies to facilitate student learning. Overall, the teachers developed a deeper understanding of student conceptions on the molecular level and further developed their PCK through the workshop experience, suggesting that a similar model might be beneficial for future professional development (Van Driel et al., 1998).

**TSPCK coursework.** Dreschler and Van Driel (2008) provided an example of research that examined teachers’ PCK after the completion of a course on PCK of acids and bases. Two years after the teacher candidates completed the course, the candidates were interviewed regarding potential changes in their PCK as an effect of the intervention. The course was not intended for listing strategies for teaching acids and bases, but rather examined the teachers’ PCK of acids and bases, in particular student learning difficulties, models of acids and bases, and how these models impacted student learning. Thus the investigation was limited to those candidates who had previously taken the course so the researchers could determine the effect of the intervention on teacher PCK (Dreschler & Van Driel, 2008).

Data were obtained via semi-structured interviews that consisted of three parts: a beginning or briefing, the main phase, and an end or debriefing for nine volunteer teachers, six male and three female, from southern and central Sweden. The researchers explored four aspects of teacher instruction of acids and bases and teacher PCK. This included the planning of acid-base lessons and how their teaching changed from one year to the next. One part focused on the textbook, another part was teacher responses to authentic student perceptions and possible causes.
Another section questioned teachers about students’ interpretations of models while the final component asked teachers to make a story line showing their satisfaction with their teaching of acids and bases from the start of their careers (Dreschler & Van Driel, 2008).

After the interviews were conducted, the information was transcribed and summaries were constructed for each teacher. Each author subsequently coded his own categories and subcategories. Tallies were kept of how many times a teacher mentioned the category in the interview. A third researcher checked the scoring of the categories to improve reliability. Next, patterns were drawn for the nine participants and tabulated for comparison. All teachers in this study found that the students had confusion in two areas of acid and base chemistry: 1) student understanding of models, and 2) the difference between the macroscopic and sub-microscopic as it pertains to acid-base chemistry (Dreschler & Van Driel, 2008).

The use of authentic student responses and analysis of textbook statements during the interviews were valuable tools in assessing the teachers’ PCK. From the data emerged two categories of teachers: 1) one group who planned on taking into consideration student learning difficulties and taught via models, and 2) the other group who planned lessons that were cheap, fun and stimulating to the teacher. In general, teachers used research-based methods and spent more time trying to improve their instruction during the first few years of teaching. Thus when they were questioned about their satisfaction with their teaching of acids and bases, it was hard to differentiate just acid and base chemistry in their story line. Teachers felt that the unit did not stand out more than the other topics. Although this showed that teacher training courses have been beneficial it would be better to have had strategies to implement the models. Limitations of this study included the difficulty in determining whether the teachers’ PCK improved as a result of the course or due to some other factor such as the effect of teaching experience (Dreschler & Van Driel, 2008).

In 2011, Aydeniz and Kirbulut assessed pre-service teachers’ PCK in electrochemistry since it is one of the most cited areas of difficulty for chemistry students. These researchers were aware that students have misconceptions in electrochemistry and that science teachers’ PCK plays a critical role in helping students overcome these misconceptions. Since there was no instrument available at the time to assess electrochemistry TSPCK, they developed the Secondary Teachers’ Scientific Pedagogical Content Knowledge Instrument (STPCK) and validated it with 31 pre-service science teachers in their junior or senior year of college (Aydeniz & Kirbulut, 2011).

The instrument was comprised of three parts consisting of 30 items. Seven items assessed the pre-service teachers’ knowledge of the curriculum, nine items assessed knowledge of instructional strategies, and 14 items measured knowledge of assessment and evaluation. One week after the administration of the exam, the pre-service teachers were brought together in groups of two to four to discuss the responses. Each response was graded on a scale from zero to ten with ten being the highest level of PCK. The cumulative responses were graded so each participant had a category such that level one meant naïve PCK, two meant developing PCK, and level three indicated sophisticated PCK. The researchers claimed that the STSPCK was a valid test yet no statistical tests results were shown to provide evidence of such. Additionally, there was no interrater reliability reported (Aydeniz & Kirbulut, 2011).

The results of the examination showed that pre-service teachers had limited PCK in electrochemistry. Teachers tended to structure lessons with emphasis on hands-on learning strategies rather than conceptual change. Moreover, the findings showed that the PCK instrument
had significant potential to provide valid and reliable information on the sophistication level of pre-service chemistry teachers’ TSPCK (Aydeniz & Kirbulut, 2011).

**PCK and curricular change.** Research conducted by Avargil, Herscovitz, and Dori (2012) examined eight chemistry teachers who implemented a context based chemistry module in Israel called “Taste of Chemistry.” The teachers who participated in this research were trained 28 hours over the summer with four eight-hour meetings during the school year. The purpose was to learn the topics of the module since they were not taught previously. The methodology consisted of guided interviews, classroom observations, and a specifically designed assessment for students partaking in the new curriculum model. Some of the teachers found they did not have the pedagogical knowledge to teach about everyday chemistry issues. One teacher indicated it was difficult to teach tables and graphs in chemistry and that she needed to develop strategies for the students to learn the information. Teachers also reported that their students had learning difficulties when it came to molecular representations (Avargil et al., 2012).

The teachers were challenged by teaching the four levels of chemistry understanding as described by the module: macroscopic, sub-microscopic, symbolic and process based, but were for the most part able to implement them into the curriculum. However, they found teaching “thinking skills” to be a difficult aspect of the new curriculum model. The teachers found it easier to explain chemistry content questions than food questions based on everyday life. Teachers who typically taught to the test found this mode of instruction difficult since there was no test bank of questions to guide the instruction. The research supported the findings of Abell (2008), who suggested being able to teach means having multiple sources from which to convey knowledge and apply to various situations. Not all teachers in this study developed new testing strategies, perhaps due to time constraints (Avargil et al., 2012).

Coenders et al. (2008) examined the content knowledge teachers wanted to acquire in transitioning to a new chemistry curriculum. This study also explored the role of pre-conceptions and the ways they could impact information integrated into one’s knowledge base. The research subjects were four male and three female qualified high school teachers with master’s degrees in chemistry, six of whom had 20 years or more of experience and one novice teacher with only two years of experience. The data included semi-structured interviews over a period of six weeks that ranged from 60-90 minutes in length. The interview responses were examined for key phrases that were tabulated for each research subject, and major themes were identified. Data had adequate interrater reliability (Coenders et al., 2008).

Some teachers found their roles were strictly limited to delivering content knowledge while others agreed that teaching chemistry involves supporting students in forming metacognitive strategies. All teachers mentioned that a full teaching load did not leave enough time to develop new learning material. Some teachers felt that developing materials should be left to professionals who had sufficient time. Teachers agreed that a course offered at the school for in-service credit would be the best option to help develop their curriculum knowledge. The teachers in this study mentioned the need to update their PCK and academic domains in order to facilitate student learning. One negative aspect of this study was there were only seven teachers sampled, so it was difficult to make generalizations (Coenders et al., 2008).
2.14 Theoretical Framework

Shulman defined the term *pedagogical content knowledge* as the knowledge for teaching a topic, meaning the “tools” utilized to teach the topic such as the best representations, explanations, and analogies. General PCK taxonomy can be divided into domain specific PCK such as chemistry or physics, which can be further subdivided into topic specific PCK such as oxidation, kinetics, or redox and electrochemistry. The construct of TSPCK has been further delineated by Loughran et al. (2006) and, more recently, Mavhunga and Rollick (2013) defined its foundational components. TSPCK defines the needed skills for subject matter knowledge transformation in a particular topic, which includes students’ prior knowledge, curricular saliency, what makes a topic easy or difficult to teach, and representations.

This study builds upon Mavhunga & Rollnick’s work by defining the TSPCK construct in a sample of experienced chemistry teachers in a professional learning community in New York. While previous studies have evaluated the effect of content knowledge on TSPCK, this study sought to show how TSPCK is related to student learning. Additionally, this study sought to examine TSPCK via tasks in conjunction with an exam as a means of assessing TSPCK. Teachers in New York State were evaluated on students’ success on standardized exams, thus this study sought to determine whether higher TSPCK levels of teachers translated into greater student outcomes within a topic. The participants in this study stated TSPCK training is limited and desired suggesting the need for programmatic changes at the pre-service and in-service levels. These improvements could be presented in the form of TSPCK specific course requirements, TSPCK modules as well as TSPCK assessments to attain certification as opposed to separate exams in content and pedagogy. Additionally, suggestions are made for professional development opportunities for in-service teachers to focus on topic specific professional development opportunities as opposed to pedagogy in general.

2.15 Conceptual Framework

TSPCK has been operationally defined as a teacher’s combined professional knowledge of content and students in a particular disciplinary domain (Hill et al., 2008). In this study, experienced chemistry teachers provided explanations for what they believed to be the big ideas and related misconceptions of the sub-discipline, as well as how they helped their students overcome misconceptions through the use of specific chemistry teaching strategies. Along with this information, teachers’ rationales for why those methods were chosen were evaluated to define TSPCK operationally in redox and electrochemistry. Additional information on past training and professional development is noted in order to provide suggestions for future generations of chemistry teachers. The framework provided by Mavhunga & Rollnick (2013) was adapted to suit a different population of teachers in a different context.

The categorical representations and teaching strategies were somewhat difficult to differentiate in this study. It seemed more appropriate to collapse those categories into one called “teaching methodologies” since the representation often times was the mode by which learning occurred. The second amendment to the original framework included combining the categories about students’ prior knowledge and alternate conceptions with the category what makes the topic difficult to teach. Students were pre-tested on the subject and showed very little prior knowledge on the topic. For these particular teachers, the alternate conceptions cited were those reported in literature as misconceptions and also concepts they had difficulty teaching. These categories were collapsed into one overarching category called “obstacles to student learning.”
Figure 2 shows the new framework developed to guide the analysis. Curricular saliency included the order of topics taught, as well as an understanding of appropriate sequence of topics, real life applications, and the extent to which the teacher taught beyond the scope of understandings assessed on the final exam.

Figure 2. Conceptual TSPCK model.
Chapter 3

Methodology

3.1 Study Overview

NRC (1996) stated that teachers have the greatest impact on students’ success. Thus, research on teachers’ PCK, the means by which teachers present content knowledge into a form that students can learn, is of high value. By acquiring information as it pertains to the development of the PCK of science teachers, the education and practice of science teaching can be advanced (Boesdorfer, 2012). Bucat (2005) recommended master teachers engage in topical case studies to demonstrate methodologies that can be utilized to teach a topic. This research addresses this issue for the topic of oxidation and reduction. The following research questions and sub-questions guided the collection of data:

1. What components of TSPCK were evidenced by the instructional design decisions experienced chemistry teachers made prior to and during instruction of redox and electrochemistry?
2. What shared patterns/trends and variations were observed among experienced chemistry in TSPCK in redox and electrochemistry?
3. How was the experienced teachers’ TSPCK related to student learning of redox and electrochemistry?

This study examined how experienced chemistry teachers leveraged their content knowledge in redox and electrochemistry and transformed it into a form of understanding that students found comprehensible. TSPCK includes students’ prior knowledge, curricular saliency, what makes some topics more difficult to learn than others, representations, and teaching strategies for the topic of study. The methodology chosen for this research was case study. A case study methodology is employed when one is trying to gain an “in-depth understanding” and since the goal of this study was to evaluate the TSPCK of high school chemistry teachers in a professional learning community, this seemed appropriate (Merrian, 1998, p. 19). Yin (1994) also suggested a case method approach when the context is part of the understanding, here the context being the students, the geographic area and state, the school, and the classroom learning space. Other studies that tried to capture the PCK of teachers have also used a case study approach (Davidowitz & Rollnick, 2011; Rollnick, Bennett, Rhemtula, Dharsey, & Ndlovu, 2008).

Subjects: Chemistry teachers in a professional learning community. This study evaluated the means by which eight New York State (NYS) experienced chemistry teachers enacted their PCK to transform chemistry content within the topics of oxidation, reduction and electrochemistry, thus this examination establishes a framework for topic specific pedagogical content knowledge (TSPCK) in redox and electrochemistry. The subjects were part of a professional learning community known as the Master Teacher Program in NYS. A Master
Teacher is a current STEM teacher who has applied and met the qualifications as determined by the State University of New York (SUNY), has achieved a high rating based on student performance, and engaged in continuous professional development (SUNY, 2013). Teachers were selected based on a variety of criteria including their scores on the PRAXIS chemistry content assessment (Praxis Series, 2003), interviews, demonstration lessons, school administrators’ letters of support, and their effectiveness as determined by the state performance review system. To be eligible, teachers had to have achieved a rating of “effective” or “highly effective,” taught 60% of more of their course load in a STEM field, and had certification and experience teaching in a STEM field for at least four years within the public education system. Science education and content experts on the SUNY faculty interviewed and evaluated potential Master Teacher candidates to evaluate their content knowledge and the strength of their PCK. To date, approximately 700 teachers in NYS hold the designation Master Teacher.

Master Teachers are required to engage in professional development opportunities beyond the normal hours of the school day, for a total of 50 hours annually, in order to increase their knowledge of content, pedagogy, and student learning. They have opportunities to engage with other Master Teachers across New York State to develop the skills that will enable them to serve as teacher leaders at the school level and are provided with a state funded stipend annually for four years (SUNY, 2013).

3.2 Operational Definitions

Teacher professional knowledge definitions. The definition of PCK has been altered and adapted over time. For the purpose of this study, the definitions and explanations set forth in Magnusson et al. (1999) will be employed since they have been commonly used by other prominent researchers in the field, including Bindemagel and Eilks (2009), De Jong et al. (2005), and Lee and Luft (2008).

Content knowledge. This refers to factual knowledge of the discipline at large such as theories and principles. In the case of chemistry, this means the knowledge one typically obtains through university-level chemistry. Content knowledge may also be acquired through professional development, post graduate coursework, or various other resources such as the textbook or internet that have multiple representations.

Curricular knowledge. This refers to knowledge of what content needs to be taught for a particular course. High school chemistry teachers are required to teach a particular curriculum specific to designated courses. Chemistry courses related to this study are described in the next section.

Pedagogical content knowledge (PCK). This refers to the knowledge a teacher possesses that enables him/her to teach the content necessary for a specific course. For the purpose of this study, PCK will encompass the tools by which teachers take their content knowledge and plan ways to enact it so students may learn chemistry concepts. It is the transformation of teacher content and curricular knowledge into a form that students can understand.

Topic specific pedagogical content knowledge (TSPCK). This refers to the knowledge a teacher possesses that enables him/her to teach the content necessary for a specific within a topic
within a discipline; herein it will describe the topics of redox and electrochemistry within the chemistry discipline.

**College course designations.** These courses are those where chemistry teachers have the opportunity to learn about the practice of teaching chemistry. They are often required in addition to content courses to earn teacher certification.

**Science methods course.** This is a teacher preparation course where teachers acquire the skills necessary to be a teacher of science. A methods course provides effective teaching strategies, techniques for planning, and assessment skills, which constitute preparation needed for teachers prior to their student teaching. The foundations and strategies necessary to develop PCK and facilitate student learning are typically taught, such as demonstrations, laboratory activities, inquiry instruction, cooperative learning, representations of content, identification of misconceptions, and relevant research or support for the aforementioned methods. A science methods course may be taken at either the undergraduate or graduate level.

**Chemistry PCK course.** This refers to a teacher preparation course designed to teach knowledge of curriculum, knowledge of student misconceptions, and pedagogical methods for transforming content knowledge into instruction via analogies, representations, and other means to address misconceptions.

**High school chemistry course designations.** The following describes the types of courses taught by the experienced chemistry teachers in this study. The International Baccalaureate (IB) curriculum is not discussed due to the fact that none of the subjects worked in an IB school or had knowledge of the IB program.

**Advanced Placement (AP) Chemistry.** This is a particular class that follows the curriculum developed by the College Board that culminates with the Advanced Placement Chemistry Examination. It is considered to be equivalent to a college level chemistry course (College Board, 2016).

**Regents Chemistry.** This is a particular class that follows the curriculum developed by NYS that culminates with the Physical Setting Chemistry Regents Examination (New York State Education Department [NYSED], 2013). The course includes the following topics: introduction to chemistry, atomic structure, periodic table, formulas and equations, mathematics of chemistry, bonding, gases, chemical kinetics and equilibrium, acids and bases, redox and electrochemistry, organic and nuclear chemistry. Additionally, students are required to complete 1200 minutes of laboratory investigations to be able to take the Regents Examination at the end of the school year. Table 3 summarizes the curriculum and outcomes that Regents level students are expected to achieve specifically related to the topics of redox and electrochemistry. The first column of the table provides the major understandings or performance expectations the teachers were responsible for teaching. The second column provides the skills the students should be able to do as a result of instruction. Finally, the real world applications are avenues the teachers were expected to link the curriculum for their students.
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<th>Major Understandings</th>
<th>Student Skills</th>
<th>Real-World Connections</th>
</tr>
</thead>
<tbody>
<tr>
<td>An oxidation-reduction (redox) reaction involves transfer of electrons.</td>
<td>Determine a missing reactant or product in a balanced equation.</td>
<td>- Electrochemical cells</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Corrosion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Electrolysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Photography</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Rusting</td>
</tr>
<tr>
<td>Reduction is the gain of electrons.</td>
<td></td>
<td>- Smelting</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Leaching (refining of gold)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Thermite reactions (reduction of metal oxides, ex aluminum)</td>
</tr>
<tr>
<td>A half-reaction can be written to represent reduction.</td>
<td>Write and balance half-reactions for oxidation and reduction of free elements and their monatomic ions.</td>
<td>- Recovery of active non-metals for ex. (I₂)</td>
</tr>
<tr>
<td>Oxidation is the loss of electrons.</td>
<td></td>
<td>- Patina (Copper-Statue of Liberty)</td>
</tr>
<tr>
<td>A half-reaction can be written to represent oxidation.</td>
<td></td>
<td>- Metallurgy of ion and steel</td>
</tr>
<tr>
<td>In a redox reaction the number of electrons lost is equal to the number of electrons gained.</td>
<td></td>
<td>- Electroplating</td>
</tr>
<tr>
<td>Oxidation numbers (states) can be assigned to atoms and ions. Changes in oxidation numbers indicate that oxidation and reduction have occurred.</td>
<td></td>
<td>- Patina (Copper-Statue of Liberty)</td>
</tr>
<tr>
<td>An electrochemical cell can be either voltaic or electrolytic. In an electrochemical cell, oxidation occurs at the anode and reduction at the cathode.</td>
<td>Compare and contrast voltaic and electrolytic cells.</td>
<td>- Metallurgy of ion and steel</td>
</tr>
<tr>
<td>A voltaic cell spontaneously converts chemical energy to electrical energy.</td>
<td>Identify and label parts of a voltaic cell (Cathode, anode, salt bridge) and direction of electron flow, given the equation.</td>
<td>- Electroplating</td>
</tr>
<tr>
<td>Al electrolytic cell requires electrical energy to produce chemical change. This process is known as electrolysis.</td>
<td>Identify and label parts of an electrolytic cell (anode, cathode) and direction of electron flow, given the reaction equation.</td>
<td>- Metallurgy of ion and steel</td>
</tr>
</tbody>
</table>
3.3 Context

This study was designed to examine the knowledge and practices of experienced high school chemistry teachers in the areas of redox and electrochemistry as well as an analysis of how teachers’ subject matter knowledge in these areas impacted student learning. The teachers in this study followed a variety of pathways to complete the requirements for certification as chemistry teachers. Since the requirements for teacher certification vary drastically from state to state in the U.S., the following section outlines the state certification requirements along with the pathways to obtain certification in NYS.

State certification requirements. The No Child Left Behind Act of 2001 called for teachers to be highly qualified to teach their content area to ensure that all students in the U.S. are taught effectively (U.S. Department of Education, 2001). In NYS there are various certification pathways by which a teacher may become qualified to teach chemistry. The Office of Teaching Initiative within the NYSED administers the certification of teachers. The following information outlines all relevant certification information as it pertinent to the field of chemistry. In NYS, certifications are granted to specific grade level bands. Science certificates for teaching high school students fall under the adolescent license category that includes grades 7-12. A separate middle school grade level certificate is issued for grades 5-9 and childhood for grades 1-6 (NYSED, 2015). Since the large majority of teachers on Long Island achieve certification through an approved teacher preparation program, the next section will describe this process.

Traditional certification pathways. According to the NYSED, the requirements for an approved chemistry teacher preparation program include completion of an NYS Registered Program for grades 7-12. A registered program is one that the NYSED has evaluated and has met all qualifications for teacher certification. Upon completion of requirements, the higher educational institution’s certification officer is required to make an online statement that the candidate has met all the qualifications required by the university program (NYSED, 2015).

To become certified, in addition to the institutional recommendation, a candidate must successfully complete three exams: the Liberal Arts and Sciences Test (LAST), a Written Assessment of Teaching Skills (ATS-W), and the Content Specialty Test (CST), though they need not be taken in any particular order (NYSED, 2015). The CST evaluates the candidate’s knowledge of the subject for which he or she is seeking certification through the use of multiple-choice questions. The LAST assesses liberal arts and science skills through multiple choice questions as well as a written assignment in the areas of science, mathematics, and technological processes, historical and social scientific awareness, artistic expression and the humanities, communication and research skills, written analysis and expression. The ATS-W is also a multiple choice and written response test that assesses chemistry teachers preparation to teach students in grades 7-12, in areas including student development and learning, instruction and assessment, the professional environment, instruction, and assessment (NYSED, 2015).

NYS professional development requirements. As of 2004, the certification requirements in NYS changed. The provisional certification, previously an entry-level certification that led to permanent certification, was eliminated (NYSED, 2015). The new law required that an initial certification served as an entry-level certificate leading to a professional certificate. The professional certificate remains valid so long as the candidate completes 175 professional
development hours during a five-year cycle. Previously, the permanent certification did not require professional development hours. Thus, NYS teachers certified prior to the year 2004 are not required to engage in any professional development in content or pedagogy. Those certified after this time first obtain their initial certificate and after five years can apply for their provisional certificate; they are subsequently required to participate in professional development in accordance with the individual teacher’s district guidelines. NYSED offers guidance and suggestions to districts but does not specify the amount of time dedicated to content or pedagogical learning activities. Individual districts in NYS must create a professional development plan that includes activities to assist teachers in developing subject matter knowledge, as well as teaching and assessment methods and skills for managing the classroom (NYSED, 2015). New provisions of the Every Child Succeeds Act, formally No Child Left Behind, allows for the funding of “academies” for teacher preparation independent of traditional higher education programs (Sawchuk, 2016).

### 3.4 Participants

**Selection of subjects.** The subjects were selected based on their status as experienced chemistry teachers in a professional learning community, the NYS Master Teacher Program. The Master Teacher Program is a state wide collaborative network of high performing STEM teachers that share their expertise to improve STEM education in the U.S. (SUNY, 2013). Master Teachers are required to engage in professional development opportunities to increase their knowledge of content, pedagogy and student learning. They have opportunities to engage with other Master Teachers across the state to develop the skills that enable them to serve as teacher leaders at the school level. They offer their support in the form of mentoring to pre-service and early career teachers.

The subjects for the current study were employed in various suburban school districts. Teachers voluntarily provided consent and obtained administrative consent to participate in this study. Teachers were initially asked via email and given an overview of the time commitment and responsibilities the study would require. Each school district was required to report demographic information regarding the student population and enrollment, which was available for public viewing and is a part of the NYS School Report Card (NYSED, 2017a). The Report Cards also contained data regarding state assessment scores. Table 4 summarizes the demographic data for the school districts of the chemistry teachers in the study. The students of the teachers in this study completed a high stakes chemistry assessment at the culmination of the school year. The data in Table 4 provide demographic information of students in the subjects’ district tested. All districts varied in size but all had somewhere between two to three hundred students taking the exam. Some teachers taught in the same school district.
Table 4
*Chemistry Teachers’ Student Demographics by District* (NYSED, 2017a)

<table>
<thead>
<tr>
<th>Chemistry Student Information</th>
<th>Margene &amp; Alby</th>
<th>Sarah &amp; Benjamin</th>
<th>Barbara</th>
<th>Joey</th>
<th>Roman</th>
<th>Don</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number Tested</td>
<td>214</td>
<td>270</td>
<td>211</td>
<td>208</td>
<td>269</td>
<td>284</td>
</tr>
<tr>
<td>General Education Students</td>
<td>210</td>
<td>268</td>
<td>207</td>
<td>203</td>
<td>262</td>
<td>279</td>
</tr>
<tr>
<td>Students with Disabilities</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>American Indian or Alaskan Native</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Asian or Native Hawaiian/Other Pacific Islander</td>
<td>8</td>
<td>25</td>
<td>1</td>
<td>14</td>
<td>43</td>
<td>22</td>
</tr>
<tr>
<td>Black or African American</td>
<td>19</td>
<td>42</td>
<td>1</td>
<td>9</td>
<td>44</td>
<td>4</td>
</tr>
<tr>
<td>Hispanic or Latino</td>
<td>48</td>
<td>74</td>
<td>16</td>
<td>26</td>
<td>46</td>
<td>19</td>
</tr>
<tr>
<td>White</td>
<td>134</td>
<td>172</td>
<td>195</td>
<td>159</td>
<td>132</td>
<td>237</td>
</tr>
<tr>
<td>Female</td>
<td>121</td>
<td>155</td>
<td>121</td>
<td>102</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>Male</td>
<td>93</td>
<td>115</td>
<td>97</td>
<td>106</td>
<td>129</td>
<td>144</td>
</tr>
<tr>
<td>English Language Learners</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Economically Disadvantaged</td>
<td>88</td>
<td>94</td>
<td>16</td>
<td>35</td>
<td>104</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 5 summarizes the Regents examination pass and mastery rates for the school districts of the chemistry teachers based on 2013-2014 School Report Cards (NYSED, 2015b). The passing score is sixty-five percent or greater and mastery is a score of eighty-five percent or greater. In addition, the percent of students who receive free or reduced lunch are indicated. Margene and Alby have the greatest number of students receiving free and reduced lunch followed by Sarah and Benjamin. Joey and Don work in school districts with a relatively small percentage of students receiving free and reduced lunch. The percentage of high school population indicates the population of students in the school who took the chemistry Regents exam during the 2015-2016 academic year. This was calculated by taking the number of students who actually took the exam divided by the total number of students enrolled in the high school to represent the percentage of the population who completed the exam. As most high schools are four-year schools, the highest percentage possible would be 25% taking the exam. Roman’s school district only had 59% of the students pass the exam however this is significant considering 20% of the population actually completed the course. This is high considering 39% of the students received free and reduced lunch. When looking at Margene and Alby’s school, the pass rate was higher at 75% but only 8% of the population took the exam. Don and Barbara had a very similar pass rate but Don had a higher percentage of students taking the exam.
Table 5
*Regents Chemistry Exam Passing Rates for School Districts of Participants* (NYSED, 2015b)

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Passing Percentage</th>
<th>Mastery Percentage (&gt;85)</th>
<th>% Free/Reduced Lunch of Regents Chemistry Students</th>
<th>Percentage of High School Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Margene &amp; Alby</td>
<td>75</td>
<td>8</td>
<td>41</td>
<td>8</td>
</tr>
<tr>
<td>Sarah &amp; Benjamin</td>
<td>88</td>
<td>24</td>
<td>35</td>
<td>15</td>
</tr>
<tr>
<td>Barbara</td>
<td>80</td>
<td>27</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>Joey</td>
<td>90</td>
<td>32</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td>Roman</td>
<td>59</td>
<td>13</td>
<td>39</td>
<td>20</td>
</tr>
<tr>
<td>Don</td>
<td>79</td>
<td>25</td>
<td>8</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 6 presents an overview of the education levels and degrees obtained by the chemistry teachers. Additionally, the years of teaching experience of each candidate, the amount of time teaching in his or her current school, and years of teaching chemistry are provided. Notably, only two of the eight teachers, Margene and Joey, had earned undergraduate degrees in chemistry. Only three subjects had taken a course in physical chemistry in college: Margene, Benjamin and Joey. Only two teachers have degrees in chemistry and while other subjects do not, they are all certified to teach chemistry in New York State. This is consistent with previous research examining chemistry teachers in the United States which reported only one in three teachers of chemistry actually possessed a degree in the field (Rushton, Dewar, Ray, Criswell, & Shah, 2016).
<table>
<thead>
<tr>
<th>Research Subject</th>
<th>Years Teaching Any K-12 Level</th>
<th>Years Teaching Chemistry</th>
<th>Years Teaching in Current School</th>
<th>Bachelor’s Degree</th>
<th>Master’s Degree</th>
<th>Physical Chemistry Taken in College</th>
<th>Post Master’s Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Margene</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>Chemistry</td>
<td>Liberal Arts</td>
<td>Yes</td>
<td>Geology</td>
</tr>
<tr>
<td>Alby</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>Biology</td>
<td>No</td>
<td>PhD in progress</td>
<td>Geology</td>
</tr>
<tr>
<td>Sarah</td>
<td>8</td>
<td>5</td>
<td>5</td>
<td>Biology</td>
<td>No</td>
<td>PhD in progress</td>
<td>Geology</td>
</tr>
<tr>
<td>Benjamin</td>
<td>12</td>
<td>9</td>
<td>9</td>
<td>Communications/ Physical Therapy</td>
<td>Yes</td>
<td>Doctorate Physical Therapy</td>
<td>Geology</td>
</tr>
<tr>
<td>Barbara</td>
<td>28</td>
<td>26</td>
<td>26</td>
<td>Marine Science</td>
<td>No</td>
<td>PhD in progress</td>
<td>Geology</td>
</tr>
<tr>
<td>Joey</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>Chemistry</td>
<td>Gifted Education</td>
<td>Yes</td>
<td>N/A</td>
</tr>
<tr>
<td>Roman</td>
<td>12</td>
<td>8</td>
<td>12</td>
<td>Biology</td>
<td>No</td>
<td>Technological Systems</td>
<td>N/A</td>
</tr>
<tr>
<td>Don</td>
<td>28</td>
<td>13</td>
<td>17</td>
<td>Biology</td>
<td>No</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Table 7 provides information regarding each subject’s teaching requirements. This includes the level of course taught. Additionally, the grade level of the students in the course is listed along with the number of periods a week for each class. A typical class is about 40 minutes. The amount of course time spent on the topic of interest, redox and electrochemistry, is listed. Additionally, the teaching style of the teacher for this unit is listed. The teachers had the option of choosing traditional lecture, flipped videos, textbook assignments, and other. Most in-depth information regarding explicit instruction was determined via the interviews.

Table 7: Teaching Assignments and Instructional Techniques of Chemistry Teachers

<table>
<thead>
<tr>
<th>Research Subject</th>
<th>Number of Chemistry Classes Taught</th>
<th>Level of Class Taught</th>
<th>Average Class Size</th>
<th>Grade Level of Students</th>
<th>Number of Periods per Week</th>
<th>Number of Periods Spent Teaching Redox, Electrochemistry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Margene</td>
<td>2</td>
<td>AP</td>
<td>26.5</td>
<td>10-12</td>
<td>7-8</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>R</td>
<td>28</td>
<td>10-12</td>
<td>7-8</td>
<td>15</td>
</tr>
<tr>
<td>Alby</td>
<td>3</td>
<td>R</td>
<td>28</td>
<td>10-12</td>
<td>7-8</td>
<td>14</td>
</tr>
<tr>
<td>Sarah</td>
<td>3</td>
<td>R</td>
<td>25</td>
<td>10</td>
<td>7-8</td>
<td>16</td>
</tr>
<tr>
<td>Benjamin</td>
<td>3</td>
<td>R</td>
<td>25</td>
<td>11</td>
<td>7-8</td>
<td>25</td>
</tr>
<tr>
<td>Barbara</td>
<td>1</td>
<td>R</td>
<td>29</td>
<td>10</td>
<td>7-8</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>AP</td>
<td>19</td>
<td>11</td>
<td>7-8</td>
<td>12</td>
</tr>
<tr>
<td>Joey</td>
<td>2</td>
<td>R</td>
<td>27</td>
<td>10</td>
<td>7-8</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>AP</td>
<td>20</td>
<td>12</td>
<td>7-8</td>
<td>20</td>
</tr>
<tr>
<td>Roman</td>
<td>2</td>
<td>R</td>
<td>23</td>
<td>10</td>
<td>7-8</td>
<td>15</td>
</tr>
<tr>
<td>Don</td>
<td>2</td>
<td>R</td>
<td>25</td>
<td>10-12</td>
<td>7-8</td>
<td>15</td>
</tr>
</tbody>
</table>

*AP indicates Advanced Placement Chemistry and R indicates Regent Chemistry

The research subjects all obtained certification through an approved teacher preparation program. Such a program allows a candidate to teach a particular content area and grade band, for example, chemistry in grades 7-12. In NYS, there are primary and secondary certifications. The secondary certification is provided to a teacher who already holds a current teaching certificate in the state and has successfully completed core content of 30 semester hours in chemistry as well as the state content exam in that subject. The requirements for certification have changed over time, and depending upon the time of certification, as little as twelve chemistry semester hours could have been enough to meet the state requirement for a secondary certification in chemistry. Since the requirements for secondary certifications have changed over time, some of the research subjects received secondary certification when only 18 credits of chemistry were required. Table 8 below summarizes the certification credentials for the chemistry teachers in the study. Five of the experienced teachers held their primary certifications in biology.
### Table 8
**Certifications of Chemistry Teachers**

<table>
<thead>
<tr>
<th>Research Subject</th>
<th>Primary Certification</th>
<th>Secondary Certification</th>
<th>Pathway to Achieve Certification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Margene</td>
<td>Chemistry</td>
<td>N/A</td>
<td>U</td>
</tr>
<tr>
<td>Alby</td>
<td>Biology</td>
<td>Chemistry</td>
<td>M</td>
</tr>
<tr>
<td>Sarah</td>
<td>Biology</td>
<td>Chemistry</td>
<td>M</td>
</tr>
<tr>
<td>Benjamin</td>
<td>Chemistry</td>
<td>Biology</td>
<td>M</td>
</tr>
<tr>
<td>Barbara</td>
<td>Biology</td>
<td>Chemistry, General Science</td>
<td>O</td>
</tr>
<tr>
<td>Joey</td>
<td>Chemistry</td>
<td>Gifted Education Extension</td>
<td>U</td>
</tr>
<tr>
<td>Roman</td>
<td>Biology</td>
<td>Chemistry</td>
<td>M</td>
</tr>
<tr>
<td>Don</td>
<td>Biology</td>
<td>Chemistry, Earth Science and General Science</td>
<td>U</td>
</tr>
</tbody>
</table>

- U indicates that the teacher completed an undergraduate program leading to a bachelor’s degree and teaching credential. M indicates that the teacher completed a master’s program that also awarded a teaching credential. O indicates other method.

### 3.5 Research Design and Methodology

This research employed a case study approach in defining the construct of TSPCK in redox and electrochemistry. The unit of analysis for this case study was eight experienced chemistry teachers in a professional learning community. The use of the case study was intended to elicit theoretical insights as well as practical policy recommendations for the preparation and professional development of chemistry teachers (Patton, 1990). Patterns and themes were identified across participants within the case. The goal was to develop a modified *theory of planned action*, where inputs for chemistry teacher development might be matched with outcomes and impacts (Patton, 1989). These impacts were explored in terms of student understanding and how the chemistry teacher approached the teaching of this particular topic.

To answer the research questions, data were collected from a variety of sources. Since this study intended to examine the TSPCK of experienced chemistry teachers, data were collected from their students to determine how well the teachers were able to transfer their content knowledge into student knowledge. This first phase of data collection involved students’ completion of pre- and post-content examinations in the topics of oxidation, reduction and electrochemistry. This part of the methodology showed that the students started the unit with very little prior knowledge. The second, third, and fourth phases of the study focused on the teachers themselves. The second phase of the research involved obtaining background information and context and beliefs for teaching through a questionnaire (Banilower et al., 2013). In the third phase, the teachers completed a TSPCK exam. The fourth phase consisted of semi-structured interview tasks to allow teachers to explicitly reveal their TSPCK in redox and electrochemistry. The data were analyzed and compared for the purposes of data triangulation.
Phase one: Student assessment. A pre-/post-assessment was prepared using previous Chemistry Regents Examination questions for the oxidation, reduction, and electrochemistry unit (Appendix A). The Regents Exam questions were created by experienced teachers and went through an extensive validation process and were field tested prior to appearing on the state assessment. Teachers administered the pre-test to their students before the unit was taught. The exam was piloted on a student population of ninety-one Regents Chemistry students and demonstrated adequate reliability (Cronbach’s $\alpha = 0.82$), so the test was administered to students in Regents Chemistry courses (Cortina, 1993). The chemistry teachers administered the pre-test as a means to assess prior knowledge of the subject. At the conclusion of the unit, the same test was provided as a post-test.

Phase two: Teacher background questionnaire. This phase consisted of research participants completing a questionnaire pertaining to their science teaching background and beliefs (Appendix B). The instrument was adapted from the 2012 National Survey of Science and Math Education Science Teacher Questionnaire (Banilower et al., 2013). The questionnaire was digitized using the Qualtrics survey program and sent to the research participants via an electronic link. The adapted survey contained 24 questions regarding the education, certification, and professional development of the teacher in the areas of oxidation, reduction, and electrochemistry. Additionally, specific information regarding the participants’ instructional decisions as they related to the particular unit of study was elicited. Other researchers have used questionnaires to obtain data from their subjects in this area, including Park, Yang, Chen, and Jung (2011), and Tepner and Dollny (2011). The reason for using this instrument was to determine whether shared patterns arose in the TSPCK of the individual teachers, and the survey responses provided possible explanations.

Phase three: Teacher TSPCK exam. The next phase of the study called for teachers to complete a TSPCK exam (Appendix C, adapted from Rollnick & Mavhunga, 2014). The TSPCK exam was developed for a population of teachers in South Africa. Considering the differences in content and student characteristics between the sample investigated in this study and the original South African sample, the instrument needed to be modified in order to assess the TSPCK of the teachers based on the content they actually teach. The original instrument contained more depth of knowledge than what is taught in a typical Regents chemistry course. While in South Africa the teachers seem to possess a more specialized form of content knowledge, as was mentioned in the literature review, only two teachers in this study had a degree in chemistry, thus modifications were necessary.

The TSPCK exam was piloted on three different teachers and modifications were made, in agreement with chemistry and science education faculty experts, to align the exam with appropriate curriculum-based content taught by teachers in this sample. Additionally, content validity was obtained by asking the teachers to state what they thought the questions were asking to ensure the intended question was answered in the way the researcher intended. The TSPCK exam responses were coded to align with the particular component of TSPCK they assessed. The use of these codes allowed for preliminary provisional coding by the researcher (Creswell, 2012), that is, anticipated categories were elicited from previous research yet revised in response to the data. The coding utilized was similar to that used by Dreschler and Van Driel (2008) as an effective means of transcribing chemistry teacher knowledge and beliefs. These codes allowed for immediate identification of teacher beliefs and behaviors that applied to various constructs associated with electrochemistry.
In the original instrument, a rubric was used to access the teachers’ PCK in each of the five components, with each component scored on a scale of one through four, one being limited and four being exemplary. Each question related to one specific component and was scored as a single item, thus the entire test was only five questions. In additional to Mavhunga and Rollnick, rubrics have been used to represent the PCK of teachers holistically (Park & Oliver, 2008).

The original intent of the researcher was to use the same rubric to analyze the results, but the coding structure and rubric did not align with the curriculum taught in New York and was not applicable. From the exam, components were coded and selected by the researcher to identify shared patterns in TSPCK. Another change involved the scoring scale. While some previous studies that have explored PCK included four categories: limited, basic, proficient and exemplary, the participants in this study were all rated as highly effective by their school districts prior to acceptance into the professional learning community and thus entered with some level of PCK. Consequently, the “limited” category was deemed unnecessary.

**Phase four: Teacher interview tasks.** The last phase consisted of interviews with each research participant to gain an understanding of how PCK in redox and electrochemistry guided decision-making. The interview format was chosen because, as Seidman (2013) explained, the purpose of research through interview is to draw information from individuals because they are of worth. The participants in this study were experienced chemistry teachers and as such their “story” is of great interest to the science education community (Bucat, 2005). Hashweh (2005) described how teacher “pedagogical constructions” are topic specific (Hashweh, 2005, p. 277).

A standardized open-ended interview protocol was developed and validated with three expert university chemistry faculty members. The interview was then piloted on three separate chemistry teachers. The interviews were transcribed and then evaluated by the content experts. Modifications and suggestions were made to improve the quality of responses obtained by the interview tasks. Additionally, by asking the same questions of the participants regarding their TSPCK (Appendix D), interviewer effects were minimized and the interviews were highly focused (Patton, 1990). Finally, member checking was performed in follow-up interviews with two participants to validate responses (Creswell, 2012). Additionally, as this was a convenience sample, any ambiguities were clarified by asking the subjects directly what they wrote or intended from a quote to ensure proper interpretation of results.

**Data coding.** The interviews were coded to identify teacher knowledge and beliefs about redox and electrochemistry. The initial coding utilized was similar to that used by Mavhunga (2012). The use of these codes allowed preliminary provisional coding by the researcher (Creswell, 2012; Miles & Huberman, 1994), that is, anticipated categories were elicited from previous research yet revised and modified in response to the data. These codes allowed for immediate identification of teacher beliefs and behaviors that applied to various constructs associated with chemistry teacher PCK. The initial codes included: student prior knowledge, curricular saliency, conceptual teaching strategies, what makes the topic easy or difficult to teach, and representations and analogies. The original units showed much overlap, which one can understand due to the complex nature of PCK. For instance, many teachers used certain representations and demonstrations as the means for concept development. While coding, it became unclear if this fell under the representation code or the conceptual learning strategy code since the representation was being utilized as a strategy for student learning.

For the purposes of validity and to create alignment in coding, the following themes emerged: teaching methodologies, curricular saliency and obstacles to student learning. The
curricular saliency theme incorporated all the planning and instruction of the unit, thus knowledge of how the teacher planned to teach the curriculum, including the instructional sequence and how much time spent on each component of the curriculum along with what topics needed to be taught prior to the unit. This also included plans for teaching real world applications and time allotted for standardized test prep/final exam, in this case the Regents examination.

The second theme was obstacles to student learning which incorporated teacher knowledge of misconceptions, alternate conceptions, as well as what students find difficult to learn. As was stated previously, one of the reasons students find chemistry to be difficult is due to the threefold representation of chemistry concepts including macroscopic, sub-microscopic and symbolic (Johnstone, 2009). The final theme was teaching methodologies and included everything the teacher actually does in the class setting to facilitate student learning such as representations, demonstrations, inquiry based activities, laboratories, practice, etc. These three themes form the working TSPCK construct for this study, as summarized in Figure 3.

![Figure 3. TSPCK coding process.](image)

3.6 Protection of Human Subjects

The purpose of the study is to determine ways to improve the preparation and instruction of chemistry teachers. It was anticipated that subjects would be willing to share their experiences in order to improve the PCK of current and future chemistry teachers. The confidentiality of the subject participants was ensured by not identifying the participants themselves, their schools, or the cities in which the schools were located. In addition, no other individual would know the identity of the subjects. Tape recordings of the subjects and notes were stored in a locked cabinet and all tapes and interview responses were destroyed at the conclusion of the study. There was no risk or potential harm for consenting adults through participation in the study. All protocol for informed consent was obtained and followed closely. This study was approved by Stony Brook University’s Institutional Review Board (#577014-2). The recruitment letter and participant consent form may be found in Appendix E.
Chapter 4

Results

4.1 Introduction

This chapter introduces the subjects of this study, including information that may have affected their TSPCK such as years of experience and professional development including workshops and college courses, which was gathered though the background survey. Following the subject composite, a comparison of teachers’ TSPCK will be examined through results of the TSPCK exam. The TSPCK of each subject was further evaluated through interview tasks. Student outcome data are analyzed and related to teacher and school district characteristics. The chapter culminates with a TSPCK construct and score for each teacher along with common trends and emerging themes. The following research questions and sub-questions guided the collection of data:

1. What components of TSPCK were evidenced by the instructional design decisions experienced chemistry teachers made prior to and during instruction of redox and electrochemistry?
2. What shared patterns/trends and variations were observed among experienced chemistry in TSPCK in redox and electrochemistry?
3. How was the experienced teachers’ TSPCK related to student learning of redox and electrochemistry?

4.2 Subject Composites

Margene. Margene had been teaching chemistry in a high need school district for eleven years. She earned her bachelor’s degree in chemistry and master’s degree in liberal arts and was taking postgraduate coursework in geology. Her primary area of certification was chemistry and she held no additional certifications. Margene attended numerous professional development events, over 35 hours in the prior three years, including attendance at workshops on science and science teaching, and she participated in a professional learning community focused on science teaching and learning. She had presented at regional, state and national science teacher conferences, despite her district’s willingness to pay only part of the costs associated with these conferences.

Margene had taken classes for graduate credit in chemistry content and pedagogy in the previous four to six years. In the past three years, she had taken coursework in pedagogy in general and science content other than chemistry. She did not take any courses in PCK but would be interested if one were available in her area. She had taught AP chemistry for eight years, typically with classes of 27 students comprised of mostly tenth graders.
Alby. Alby had been teaching for ten years, five in chemistry. He obtained a bachelor’s degree in biology, his master’s in teaching and was pursuing his Ph.D. in science education. His primary certification was biology and his secondary certification was chemistry. Alby had never taught AP or college level chemistry. His average class size was 29. He taught in the same high need school district as Margene.

Alby had attended over 35 hours of professional development over the previous three years including regional and state conferences, local conferences, and teaching professional development courses in his school. His district enabled him to attend professional development and some of the cost was covered by his school district. Over the prior three years he had taken courses on chemistry content and pedagogy, science content in other disciplines, and pedagogy in general. Alby had taken courses in PCK and was interested in taking additional PCK courses if they were offered locally. In the past three years he had supervised a student teacher, was formally assigned as a teacher mentor, taught in-service courses in his school, and led a professional learning community.

Sarah. Sarah was a 34-year-old female who had taught biology for eight years and chemistry for five in a high need school district. She taught Regents chemistry to an average class size of 25 students and had never taught a higher-level chemistry course such as AP or IB. She obtained her bachelor’s degree in biology and master’s degree in teaching biology, thus her primary certification was biology and secondary certification was chemistry. She was pursuing her Ph.D. in science education.

Sarah had attended less professional development than the other teachers, about six to 15 hours over the past three years when she attended a workshop and a regional and state science teacher’s association conference. She indicated she was not able to find professional development specifically designed to improve her chemistry instruction but if available her school district would provide funding. The last chemistry content course she took was approximately ten years prior. She had taken graduate courses in pedagogy, science content in other disciplines, and pedagogy in general in the previous three years. She had never taken a PCK course in chemistry but would be interested if one were offered.

Benjamin. Benjamin was a 51-year-old male and had been teaching Regents chemistry for 12 years, nine of which were in his placement at the same high need school district as Sarah. He received his bachelor’s degree in communications and physical therapy, his master’s degree in secondary education and a doctorate in physical therapy. His primary certification was chemistry and he held additional certifications in biology and general science. In his district, 86% of the students passed the Regents chemistry exam and of all the districts included in the study, his had the second highest mastery rate at 31%. His class size average was 25 students.

Regarding professional development, Benjamin had difficultly finding professional development in chemistry. His school district provided funding when he was interested in attending a conference. Benjamin was not interested in taking a PCK course for chemistry. He had not received feedback about his teaching from a mentor, nor had he served as a mentor or supervised a student teacher in the past three years.

Barbara. Barbara had been teaching for 28 years, 26 of which were chemistry. Barbara received a bachelor’s degree in marine science, master’s in secondary education, and was pursuing her Ph.D. in science education. Her primary area of certification was biology and she received secondary certification in chemistry and general science. Barbara taught AP and honors
level chemistry in a suburban school. Her Regents average class size was 29 students and average AP class size approximately 19. Of all of the Master Teachers’ school districts, Barbara’s school district as a whole had the highest Regents chemistry passing rate at 90% and third highest mastery rate at 29%. Barbara reported the least amount of professional development attended at six to 15 hours over a three-year period. This may be due to the fact that she was retiring within a year of the study and had been teaching longer than all of the other subjects. Over the years Barbara had been a supervisor to student teachers and served as a mentor to other science teachers in her building. Additionally, she was an item writer for the Regents chemistry exam.

**Joey.** Joey had worked for eleven years in an affluent school district teaching honors and AP chemistry. He obtained a bachelor’s degree in chemistry education and a masters degree in gifted education. His certification was chemistry along with a gifted education extension.

Joey attended numerous professional development activities, more than 35 hours over the past three year period, attending workshops on science teaching and regional and state science teacher association conferences with the financial support of his district. Although he had attended multiple professional development experiences, he found it difficult to improve chemistry instruction specifically. The last college courses taken by Joey were more than ten years ago, none of which involved PCK. Moreover, when asked if Joey would want to take a PCK course, he stated he was not interested.

**Roman.** Roman had been teaching high school biology and AP biology for twelve years. For nine years he had also been teaching chemistry since his secondary certification was in this area. He received his bachelor’s degree in biology and master’s degree in teaching biology as well as an additional master’s degree in technological systems management with an educational computing concentration. He completed his administration certification and planned to become a science director within a public school district.

Roman participated in a variety of professional experiences over the prior three years, including more than 35 hours at science workshops, national state and regional science teacher association conferences, participation in a science learning community, and service as a board member for a science teachers association. He also moderated a science education listserv, had an educational blog, and created a weekly podcast. Roman did not have difficulty finding chemistry related professional development and his district provided funding. He had never taken a course in PCK, but would be interested if offered.

**Don.** Don was a 53-year-old male who had been teaching for 28 years, 13 years of which were chemistry, in a middle class school district where his average class size was 27 students. He received his bachelor’s degree in biology and master’s degree in liberal studies. His primary area of certification was biology and he held additional certifications in Earth science, chemistry and general science – more than any of the other teachers in the study.

Don’s professional development experience over the prior three years included attendance at over 35 hours of science workshops and participation in a science learning community. Don expressed that he was able to find chemistry related professional development and if he were interested in attending his district would provide funding. As far as graduate coursework, his last college courses related to chemistry were more than 10 years ago. He had never taken a course in PCK and would not be interested in taking one. In the past three years he had supervised a
student teacher and taught in-service courses at his school district. He had also taught multiple in-service courses through a third party provider where teachers could receive college credit.

4.3 Data Analysis

To answer the research questions, evidence of TSPCK in the domain of redox and electrochemistry was evaluated via multiple data sources. The instructional design decisions the chemistry teachers made prior to and during instruction of this unit were examined to determine trends and patterns. Finally, the researcher examined the variation in TSPCK from teacher to teacher to using a refined construct for TSPCK in redox and electrochemistry. This chapter will examine the TPSCK evidenced from the data sources. First, student test data are discussed. This is followed by an examination of the responses provided by teachers on the adapted background survey (Appendix B). After this, teachers’ responses to a TSPCK exam in electrochemistry are analyzed. Lastly, chemistry teacher interview tasks responses are described and interpreted. The main goal of the four sources of data collection was to gain a comprehensive view of the TSPCK that each teacher possessed as it related to oxidation, reduction and electrochemistry.

The four sources of teacher knowledge need to be evaluated to develop a scale of TSPCK in redox and electrochemistry. Mavhunga (2012) described the sources of TSPCK as pedagogical knowledge, content knowledge, knowledge of students, and knowledge of context. One component, knowledge of students, was adapted to student knowledge. Instruments were designed to encapsulate the knowledge base to determine the summation of TSPCK for teaching electrochemistry. Knowledge of context was obtained via the modified Horizon instrument and teacher interview tasks. The student exam data on the pre- and post-test was evaluated to show growth in student content knowledge, which may be related to teacher content and pedagogical knowledge. The interview and TSPCK exam showed teacher content knowledge. The background survey along with the interview provided the student context. Finally, the interview tasks and TSPCK exam measured pedagogical knowledge. The data sources and constructs of TSPCK are summarized in Figure 4.

![Figure 4. TSPCK data sources for analysis.](image-url)
4.4 Student Exams

High school chemistry students of the research subjects completed pre-and post exams comprised of past NYS Regents exam questions on the topics of oxidation, reduction and electrochemistry (Appendix A). The pre-test was administered the first day the topic was taught. The post-test was administered after the teacher had completed instruction of the unit, approximately two to three weeks later. Student responses ($N = 357$) demonstrated adequate reliability ($\alpha = .82$). The null hypothesis stated that the median difference in pre-score and post-score was equal to zero. The data were not normally distributed according to Shapiro-Wilk’s test ($W = .978, p < .001$), therefore, a nonparametric analysis was performed using a Wilcoxon signed-rank test for non-parametric data. Wilcoxon signed-rank test is an analysis of matched pairs of data, in this case the student pre- and post-redox and electrochemistry assessment (Woolson, 1998). The pre-tests showed students knew very little regarding the topic prior to instruction. The Wilcoxon signed-ranks test indicated that post-test scores ($Mdn = 15$) were significantly higher than pre-test scores with a large effect size ($Mdn = 5$), $Z = 16.1, p < .001, r = .85$. Therefore, the null hypothesis was rejected.

Since the assessment included many items that were low level recall questions, a separate analysis was conducted for critical thinking questions ($N = 357$). Critical thinking questions were identified by performing a principal components factor analysis with Varimax rotation (factor loadings are identified in Table 9). It was the discretion of the researcher to name the constructs for each factor loading. For instance, the column labeled construct 3 of the correlation matrix (Table 9) has three items with coefficients greater than 0.3. Those item numbers: 5, 14 and 21 involved naming parts of the cell, which was the title chosen for that construct. All 25 items correlated with at least one other item with a loading of at least .30, which is significant factorability for a sample size $>350$ and power of $.80 (p < .05)$ (Faul, Erdfelder, Lang, & Buchner, 2007; Tabachnick & Fidell, 2001). Nine questions were selected across two factors loadings, as indicated in Table 10; these included questions 15, 17, 18, 19, 20, 22, 23, 24, and 25. A Wilcoxon signed-ranks test indicated that critical thinking post-test scores ($Mdn = 5$) were significantly higher than critical thinking pre-test scores with a large effect size ($Mdn = 1$), $Z = 15.8, p < .001, r = .84$. Similarly to the overall analysis, the null hypothesis that there was no pre-/post-test difference in critical thinking questions was rejected.
### Table 9

**Factor Loadings for Chemistry Content Assessment Items**

<table>
<thead>
<tr>
<th>Item</th>
<th>1 critical thinking</th>
<th>2 critical thinking</th>
<th>3 naming parts of cell</th>
<th>4 charge and energy conservation</th>
<th>5 process</th>
<th>6 balancing and activity series</th>
<th>7 identifying reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>.055</td>
<td>.077</td>
<td>.015</td>
<td>-.031</td>
<td>.733</td>
<td>.098</td>
<td>-.078</td>
</tr>
<tr>
<td>Q2</td>
<td>-.008</td>
<td>.138</td>
<td>.088</td>
<td>.286</td>
<td>.022</td>
<td>.002</td>
<td>.663</td>
</tr>
<tr>
<td>Q3</td>
<td>-.008</td>
<td>.111</td>
<td>-.178</td>
<td>.595</td>
<td>.010</td>
<td>-.112</td>
<td>.054</td>
</tr>
<tr>
<td>Q4</td>
<td>.211</td>
<td>.055</td>
<td>.142</td>
<td>.103</td>
<td>.703</td>
<td>-.059</td>
<td>.179</td>
</tr>
<tr>
<td>Q5</td>
<td>.048</td>
<td>.144</td>
<td>.863</td>
<td>.063</td>
<td>.085</td>
<td>.034</td>
<td>.043</td>
</tr>
<tr>
<td>Q6</td>
<td>.237</td>
<td>-.004</td>
<td>.164</td>
<td>.582</td>
<td>-.139</td>
<td>.216</td>
<td>.030</td>
</tr>
<tr>
<td>Q7</td>
<td>.401</td>
<td>.031</td>
<td>-.023</td>
<td>.043</td>
<td>-.141</td>
<td>.513</td>
<td>.120</td>
</tr>
<tr>
<td>Q8</td>
<td>.113</td>
<td>.243</td>
<td>.107</td>
<td>.361</td>
<td>.275</td>
<td>.190</td>
<td>-.399</td>
</tr>
<tr>
<td>Q9</td>
<td>.180</td>
<td>.124</td>
<td>.306</td>
<td>.099</td>
<td>-.044</td>
<td>.513</td>
<td>-.032</td>
</tr>
<tr>
<td>Q10</td>
<td>-.074</td>
<td>.310</td>
<td>.140</td>
<td>.516</td>
<td>.076</td>
<td>.199</td>
<td>.045</td>
</tr>
<tr>
<td>Q11</td>
<td>.287</td>
<td>-.074</td>
<td>.117</td>
<td>.592</td>
<td>.150</td>
<td>.108</td>
<td>.159</td>
</tr>
<tr>
<td>Q12</td>
<td>.184</td>
<td>.033</td>
<td>-.074</td>
<td>.026</td>
<td>.427</td>
<td>.276</td>
<td>.504</td>
</tr>
<tr>
<td>Q13</td>
<td>.021</td>
<td>.196</td>
<td>.098</td>
<td>-.095</td>
<td>.146</td>
<td>.555</td>
<td>.366</td>
</tr>
<tr>
<td>Q14</td>
<td>.070</td>
<td>.029</td>
<td>.868</td>
<td>.018</td>
<td>.106</td>
<td>.088</td>
<td>.041</td>
</tr>
<tr>
<td>Q15</td>
<td>.577</td>
<td>.025</td>
<td>.137</td>
<td>.256</td>
<td>.114</td>
<td>.218</td>
<td>-.025</td>
</tr>
<tr>
<td>Q16</td>
<td>-.019</td>
<td>.058</td>
<td>-.096</td>
<td>.327</td>
<td>.195</td>
<td>.686</td>
<td>-.171</td>
</tr>
<tr>
<td>Q17</td>
<td>.263</td>
<td>.611</td>
<td>.313</td>
<td>.073</td>
<td>-.027</td>
<td>-.035</td>
<td>-.002</td>
</tr>
<tr>
<td>Q18</td>
<td>.594</td>
<td>.159</td>
<td>.045</td>
<td>-.030</td>
<td>.144</td>
<td>.042</td>
<td>-.156</td>
</tr>
<tr>
<td>Q19</td>
<td>.489</td>
<td>.059</td>
<td>.014</td>
<td>.021</td>
<td>.075</td>
<td>.019</td>
<td>.309</td>
</tr>
<tr>
<td>Q20</td>
<td>.177</td>
<td>.652</td>
<td>.016</td>
<td>-.001</td>
<td>-.102</td>
<td>.208</td>
<td>.191</td>
</tr>
<tr>
<td>Q21</td>
<td>.377</td>
<td>.308</td>
<td>.433</td>
<td>.026</td>
<td>-.068</td>
<td>.014</td>
<td>-.071</td>
</tr>
<tr>
<td>Q22</td>
<td>.010</td>
<td>.691</td>
<td>.013</td>
<td>.119</td>
<td>.227</td>
<td>.134</td>
<td>-.033</td>
</tr>
<tr>
<td>Q23</td>
<td>.424</td>
<td>.456</td>
<td>.115</td>
<td>.120</td>
<td>.237</td>
<td>.005</td>
<td>.008</td>
</tr>
<tr>
<td>Q24</td>
<td>.527</td>
<td>.322</td>
<td>.079</td>
<td>.173</td>
<td>.094</td>
<td>.180</td>
<td>.079</td>
</tr>
<tr>
<td>Q25</td>
<td>.326</td>
<td>.344</td>
<td>.090</td>
<td>.118</td>
<td>.308</td>
<td>-.084</td>
<td>.119</td>
</tr>
</tbody>
</table>

Further quantitative analysis was performed to disaggregate results by teacher. Normalized learning gains were calculated by taking the difference between pre- and post-scores (both overall and critical thinking only) and dividing this difference by the largest possible gain, as shown below:

\[
\text{Overall normalized gain: } \frac{\text{post-pre}}{25-\text{pre}} \quad \text{Critical thinking normalized gain: } \frac{\text{post-pre}}{9-\text{pre}}
\]

Normalized gains in both categories varied by teacher as indicated in Table 10. The large values for standard deviation indicate within class variation was notable, contributing to non-normalized score distributions. The students of Joey, Barbara and Benjamin showed the greatest learning gains on critical thinking questions, while Sarah, Margene and Alby showed the smallest learning gains.
Table 10
*Student Normalized Learning Gains by Teacher*

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Number of Students Tested</th>
<th>Overall Normalized Gain</th>
<th>Critical Thinking Normalized Gain</th>
<th>Student Socioeconomic Status (School FRL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>$Mean$ $(SD)$</td>
<td>$Mean$ $(SD)$</td>
<td></td>
</tr>
<tr>
<td>Margene</td>
<td>57</td>
<td>.43 (.20)</td>
<td>.39 (.23)</td>
<td>.35</td>
</tr>
<tr>
<td>Alby</td>
<td>44</td>
<td>.30 (.25)</td>
<td>.37 (.29)</td>
<td>.35</td>
</tr>
<tr>
<td>Sarah</td>
<td>54</td>
<td>.38 (.27)</td>
<td>.29 (.33)</td>
<td>.30</td>
</tr>
<tr>
<td>Benjamin</td>
<td>67</td>
<td>.62 (.21)</td>
<td>.61 (.28)</td>
<td>.30</td>
</tr>
<tr>
<td>Barbara</td>
<td>29</td>
<td>.73 (.13)</td>
<td>.64 (.17)</td>
<td>.07</td>
</tr>
<tr>
<td>Joey</td>
<td>23</td>
<td>.62 (.17)</td>
<td>.68 (.19)</td>
<td>.08</td>
</tr>
<tr>
<td>Roman</td>
<td>60</td>
<td>.44 (.22)</td>
<td>.51 (.24)</td>
<td>.24</td>
</tr>
<tr>
<td>Don</td>
<td>20</td>
<td>.26 (.20)</td>
<td>.31 (.25)</td>
<td>.08</td>
</tr>
</tbody>
</table>

The linear relationship between critical thinking normalized gains and socioeconomic status (SES) is shown in Figure 5. A Spearman bivariate correlation analysis revealed a moderate significant correlation between student performance and socioeconomic status ($r = .26, p < .01$). Within class student variation contributed to value added outcomes in addition to teacher quality, as evidenced a general downward trend in student performance as poverty level increased.

*Figure 5.* Relationship between critical thinking normalized learning gains and socioeconomic status.

4.5 **Background Survey**

The modified background survey (Appendix B) was administered to the research subjects to gain background information on teachers prior to and during their teaching careers. The following section provides descriptive details regarding the professional development experiences of the chemistry teachers to summarize trends and patterns.
**Professional development.** After entering the profession, teachers may develop their TSPCK via professional development workshops and college courses. The research subjects were asked a series of questions related to the professional development they had attended to gain a sense of how professional development improved PCK. All teachers had taken part in professional development opportunities focused on chemistry in the previous three years. The most common way teachers received professional development was through a workshop. Three of the teachers, teacher Sarah, Benjamin, and Joey expressed that it was difficult to find professional development opportunities in chemistry. Once these teachers entered the profession, they intended to improve their practice, however, the opportunities were often limited.

Teachers were asked to give a more detailed description of the exact nature of the professional development they attended. The type of professional development least experienced was engaging in hands-on science investigations. The most common type of science professional development experience was working with other teachers of science within their school or district. Six of the teacher stated that the district would cover the cost of professional development if they wanted to attend, and two teachers, Margene and Alby, stated that the district would cover part of the cost.

**College courses.** Another means of professional development was college coursework. The research subjects were asked when they last took a formal course for college or graduate credit in each of the following areas: chemistry content, chemistry pedagogy, science content other than chemistry, pedagogy in general, and other. Most teachers in the study had been teaching ten years or longer, which would indicate that courses taken more than ten years ago were likely their methods coursework or courses they took immediately after earning teacher certification. Most teachers did not take a college course between four and ten years ago. The teachers in this program had all entered the Master Teacher program in the previous three years. Notably, there was a dramatic increase in the amount of professional development experienced during that time since the Master Teacher program provided hours of professional development opportunities for the teachers to attend. As indicated in Figure 6, the courses most commonly taken by were those related to pedagogy in general. The least common type of course was chemistry content or pedagogy as it relates to chemistry. Thus, it seems if teachers had the opportunity to take a course, they preferred a pedagogy class as opposed to a content class. Some of the teachers in this study were in a science education doctoral program, which may also account for the pedagogy courses as opposed to straight content courses.
Teachers were not required to take college courses, however, in NYS, school districts typically offer an increase in the teacher pay scale when teachers complete intervals of 30 and 60 credits beyond their masters degree or earn a Ph.D or other doctoral degree. Aside from the increase in pay there are no other extrinsic motivators for teachers to complete additional coursework. Of the teachers in this study, two teachers stated that they attended a college that offered teacher preparation courses specifically designed to provide PCK for chemistry teachers, meaning the course specifically included objectives related to knowledge of curriculum, student misconceptions and science teaching methodologies, assessment, representations, as well as the means of addressing misconceptions. Teachers were asked if they would be willing to take a chemistry course in PCK and half of them, Margene, Alby, Sarah, and Don, responded yes, while the other half responded no. Three of the four teachers who indicated they would not be interested were all over the age of 50, which could impact this decision.

**Alternate methods of professional development.** Besides workshops or conferences and college courses, the teachers engaged in other types of professional development to improve their
professional practice. The most common type of professional experience was a professional learning community, lesson study or teacher study group focused on science or science teaching. Seven of the eight participants in this study reported engaging in this form of activity, which is a chemistry specific group. Through the Master Teacher program, there was the opportunity to participate in a professional learning community. Five of the eight teachers, Alby, Sarah, Benjamin, Roman and Don had taught an in-service workshop on science and science teaching. Four of the eight teachers (Barbara, Joey, Roman and Don) had supervised student teachers in their classroom. Three of the teachers Alby, Roman, and Barbara had served as a mentor or coach for a science teacher. The next section focuses on how the teachers utilized the content and pedagogical tools they had been taught via college courses or professional development in their classrooms. Master Teachers received a stipend and were required to engage in professional development activities, thus it is understandable that the amount and type of professional development may not be applicable to all populations.

**Instructional delivery.** Teachers were asked how they delivered the content to their students for the unit on oxidation, reduction and electrochemistry. Four of the teachers Margene, Alby, Sarah and Benjamin, used flipped instruction to deliver the content to the students. Flipped instruction required the students to watch a video the night before a lesson, so that the following day students could engage in more hands on activities (Sams & Bergman, 2013). Six teachers incorporated lecture into some component of their instruction. Only one teacher, Barbara, provided students with textbook readings. Four of the teachers mentioned that they provided other instruction, as well, possibly a combination of lecture and video. It is meaningful to note that the majority of teachers were not utilizing a textbook as a means of instruction. The implication of such is that students are required to read content and thus not building literacy skills, thus their cross-disciplinary strategies may not be as strong as they should be.

**Redox and electrochemistry.** Teachers were asked to describe how they taught the unit including oxidation, reduction and electrochemistry. Figure 7 shows what percentage of teachers utilized particular methodologies. The most common type of learning experience was the teacher explaining a science idea to the whole class and students completing practice problems or a worksheet in preparation for standardized tests, tests or quizzes. The least reported activities included use of textbook and reading about science.
Next, teachers were asked to explain the types of learning experiences they provided for their students during the teaching of the unit on oxidation, reduction, and electrochemistry. All teachers indicated they questioned individual students during class activities to see if they were ”getting it.” They reviewed student work such as homework, notebooks, journals and projects, and they administered one or more quizzes and/or tests to see if students comprehended the material. They went over the correct answers to the assignments for the classes as a whole. Seven of the eight teachers stated that they assigned grades to student work, for example, homework. Six teachers stated that they had useful information from informal assessments, such as asking for a show of hands, thumbs up thumbs down, clickers, and exit tickets to assess student learning. Only two teachers administered an assessment, task, or probe at the beginning of the unit to determine what information the students already knew about subject. Many teachers utilized a variety of methods to show student learning. They all had a strategies to use to assess their students formatively and summatively.

The Horizon survey provided information on backgrounds and beliefs of the teachers. Most concerning was the inability to find chemistry specific professional development, suggesting a lack of continuing education to meet the needs of the teachers. The responses indicated that most teachers engaged in more than 35 hours of professional development in general over the past
three years, but that chemistry content courses and chemistry pedagogy courses were not as common as pedagogical strategies in general. As far as instruction, most teachers reported hands on activities, laboratories, cooperative learning, worksheets and assessments, in the form of tests and quizzes, with less emphasis on reading or textbook use. Additional means of professional development were discussed, the most common of which was participation in a professional leaning community, a sharing group created from within the Master Teachers program, or leading a workshop. Few teachers received feedback from a mentor in their content area.

The next section of this chapter focuses on the TSPCK exam each teacher completed as part of the study. While the Horizon survey provided background and more general information about each teacher’s pedagogy, the TSPCK exam provided more topic specific information to help define the TSPCK in electrochemistry for each teacher. The goal of the TSPCK exam was to provide information on how electrochemistry is taught along with the teachers’ rationales.

4.6 TSPCK Exam

This section will focus on the TSPCK exam in electrochemistry that the teachers completed. The exam was aimed at determining the teachers’ knowledge of student misconceptions, curricular saliency, knowledge of what makes the topic difficult to teach, analogies and conceptual learning strategies. The time taken to complete the test ranged from 35-60 minutes. The following sections will analyze the teachers’ responses.

Teacher awareness of student misconceptions. Literature has shown that many students have found the topic of oxidation and reduction difficult to learn. Additionally, not only did students have misconceptions, but the teachers of those students often held misconceptions (Lemma, 2013). Teachers need to be aware of student misconceptions in order to design lessons that can address those them (Al-Balush et al., 2012). The TSPCK exam (Appendix B) assessed each teacher’s ability to identify student misconceptions and preconceptions that might alter students’ ability to learn the topic. Table 11 outlines the commonly identified misconceptions. The X notation in the table indicates that chemistry teacher was aware that students held a particular misconception.
Table 11
Student Misconceptions Identified by Chemistry Teachers

<table>
<thead>
<tr>
<th>Misconception</th>
<th>Margene</th>
<th>Alby</th>
<th>Sarah</th>
<th>Benjamin</th>
<th>Barbara</th>
<th>Joey</th>
<th>Roman</th>
<th>Don</th>
</tr>
</thead>
<tbody>
<tr>
<td>The oxidation state in elemental form is the same as the charge of the monatomic ion.</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Oxidation and reduction reactions do not need to occur simultaneously.</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron flow constitutes current in electrolytes.</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrons travel through the salt bridge.</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
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</tr>
<tr>
<td>Electrons always flow left to right.</td>
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<tr>
<td>Ions of metal electrodes flow through salt bridge.</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ions flow through the wire.</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The anode is negatively charged and because of this attracts cations and the cathode is positive and because of this attracts anions.</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The anode gets smaller because it loses electrons and cathode gets bigger because it gains electrons.</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Processes at the anode and cathode are reversed.</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Students reverse signs of anode and cathode.</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atoms and ions are the same thing.</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Electroplating indicates metal phase change.</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>The electroplated metal is oxidized or reduced.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>The anode and cathode include the solutions in which they are submerged.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduction is loss of electrons.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Oxidation means decrease of oxidation number.</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>When balancing redox reactions the mass and charge both do not need to be balanced.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Oxidizing agents are oxidized and reducing agents are reduced.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Electrons always move the to negative electrode.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The most commonly identified misconceptions included the idea that electrons travel through the salt bridge and the inability to distinguish between metal atoms and ions when explaining the processes of oxidation and reduction occurring at the anode and cathode. It was notable that the most common misconceptions that teachers were able to identify were ones that students often answered incorrectly on the NYS Regents exam. Teachers were not able to identify many misconceptions identified in the literature (Garnett et al., 1990). Margene, Alby and Don were able to identify the greatest number of misconceptions and Sarah and Joey appeared to have the most difficulty with this portion of the study.

Obstacles to student learning. The TSPCK exam assessed what aspects of the topic the teachers found difficult when teaching electrochemistry, and these are represented in Table 12. It became evident that different parts of the unit presented varying levels of difficulty for each teacher. Three of the teachers explained that their students struggled to understand reduction as...
an increase in oxidation number since the term “reduction” typically means to decrease. Most teachers were able to identify one or two areas they found difficult to teach, while Margene described the most problem areas with three. Electrochemistry was considered one of the most challenging topics for students to learn, yet teachers Alby, Sarah, Benjamin, Joey and Roman were only able to identify one specific piece of information within the unit that was “difficult” to teach. Teachers were lacking in their ability to describe what was difficult for students to learn so it was unlikely their instruction was designed to assist learners in these specific aspects. Furthermore, the lack of alignment is a concern since research identifying challenging electrochemistry topics is readily accessible. While these chemistry teachers were engaging in professional development on a regular basis, there did not seem to be professional development offered in TSPCK in electrochemistry or any topic to address how to assist learners in their understanding of chemistry topics that are conceptually challenging.

Table 12

*Teacher Reported Challenges of What Makes Electrochemistry Difficult to Teach*

<table>
<thead>
<tr>
<th>Electrochemistry Concept</th>
<th>Margene</th>
<th>Alby</th>
<th>Sarah</th>
<th>Benjamin</th>
<th>Barbara</th>
<th>Joey</th>
<th>Roman</th>
<th>Don</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode loses mass and cathode gains mass in terms of atoms and ions</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Definitions are confusing and process misunderstood</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recognizing difference between free elements and ions</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balancing mass and charge</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Writing half reactions with diatomic elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Predicting products of a single replacement reaction of nonmetal atoms and metal ions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Writing half reactions when the same substance is oxidized and reduced</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Understanding the structure and function of each part of the electrochemical cells</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Cell Potentials</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Curricular saliency.** The curricular saliency of the participants was examined through the TSPCK exam to identify how the teachers sequenced the unit and connected the concepts within the unit as well as to other chemistry topics. The teachers all had a firm grasp of what the NYS curriculum required. They were able to state the major understandings associated with the NYS Core Curriculum, in particular what content was required for Regents chemistry. In fact, the majority of the teachers seemed extremely focused on teaching exactly what was in the curriculum and nothing beyond this. This may be a consequence of the fact that 40% of teachers’ Annual Professional Performance Review (APPR) rating was based upon their students’ performance on Regents exams (Moldt, 2016).
Teachers were all asked why they thought it was important for students to learn about electrochemistry. Every teacher listed the real-life or practical application of chemistry in his or her response, such as that provided by Sarah (Figure 8). Margene indicated, “[the purpose of] all science education is to learn about our surroundings. Batteries are part of our lives and at this point a necessity.” This is similar to Benjamin who indicated, it’s important for students “…to understand the basic mechanics of how a battery works and why electricity is produced as well as to understand how a battery is recharged and understand the mechanics behind it.” Joey mentioned that the topic requires students to problem solve, “like all chemistry.” This answer seemed more generic and indicated limited TSPCK.

![Figure 8. Teacher TSPCK response 1.](image)

This can be contrasted with Don’s response to this question, which showed more time and effort had gone into his thought process regarding why it is important for students to learn electrochemistry. He stated:

Electrochemistry is a fundamental concept in the study of chemistry and a precursor to concepts in physics and engineering. The movement of charged particles (in particular, electrons) in chemical reactions is what allows their cell phones to work, electric cars to run, and explains hydrogen for hydrogen cars can be derived. One major emphasis on the part of on my students throughout the course is that electrons make the world go round. The simple transfer of electrons is what is making their cell phones work as the chemicals within it undergo redox reactions. The cell phone is a perfect example of the mentality of so many students. Here they have this little box that does so much for them, but that the movement of a single electron makes changes in chemicals that can be extreme in some
circumstances. Discussing how the deadly metal sodium and poisonous chlorine gas become a salt for their popcorn due to a change in their oxidation state caused by a single electron, allowing for a compound reform with different properties and elements is important in my mind.

Another theme that emerged from various teachers was that electrochemistry is a more challenging unit than most due to the greater amount of cumulative knowledge required in order to learn it. Alby explained that students’ understanding of electrochemistry requires a thorough understanding of chemistry in general. Sarah stated, “electrochemistry is a tougher unit than most.” Similarly, many teachers explained that electrochemistry ties together many concepts previously taught throughout the year. Alby, Sarah, Barbara, Roman and Don also stated similar ideas of spiraling curriculum as a reason for why the topic is important for students to learn. Benjamin explained how it brings back the ideas of charge, energy and mass conservation. The next section explores this order in which topics were taught as a means of enabling students to gain a deeper understanding of the subject matter for the purposes of assessing the curricular saliency of the chemistry teachers.

**Instructional sequence.** Teachers were asked to state which topics they taught prior to electrochemistry along with their rationale. Barbara stated these topics included atomic structure, as students must have an understanding of the atom, the periodic table to understand the activity series, and stoichiometry for students to understand mole ratios of electrons lost and for electrolysis to be quantified. Sarah stated the difference between atoms and ions and writing and balancing equations. For those responses, a rationale was not provided. Sarah also stated atomic symbols so students can write reactions and assign oxidation numbers as well as have an understanding of solution chemistry since voltaic cells require solutions for the metal to be oxidized or reduced. Margene cited the mole unit since electrons are transferred in balancing; the difference between atoms and ions to discuss mass changes in the cell; conservation of mass; subatomic particles to explain electrons and attraction; periodicity to explain metal and nonmetal reactivities; types of reactions so students could identify when a reaction was redox; and solutions so students could identify what is aqueous and dissolved verse solid metal and salt. Alby’s response included atomic structure so that students had an understanding about atoms compared to ions, bonding, balancing moles of atoms and electrons, nomenclature in order to understand how compounds are formed, and matter and solutions to understand how ions disassociate to form an aqueous solution. Sarah’s response was very detailed and included aspects of atomic structure, matter, periodic table, formulas and equations, bonding, moles and stoichiometry, solutions, acids, bases, and salts (Figure 9).
Benjamin stated he presented all topics with the exception of nuclear and organic chemistry, which should be taught after electrochemistry. He further explained he taught many “real-life” applications at the end of the year, and if students did not have a foundation they would not be able to apply that knowledge. He stated that students should know solutions to have an understanding of electrolytes and a salt bridge as well as the difference between atoms and ions for the purpose of electrolytic and voltaic cells. Roman stated that students should know how to assign oxidation numbers because it is “hard to do anything for electrochemistry without this being known prior.” Don included atomic structure, specifically subatomic particles and structure, bonding to describe the transfer of electrons and potential for movement naming, writing chemical formula and compounds, identification of the types of reactions, and, finally, solutions to discuss the movement of ions as a feature of the galvanic cell and how solutions with ionic compounds can carry electric current.

The teachers described many of the same sub-components including atomic structure for the identification of atoms and ions. Margene, Alby, Benjamin, and Don provided the most topics with a rationale. Some teachers only provided a few examples, which could indicate they were not aware of how these topics connected. This section focused on the topics that need to be taught prior to instruction electrochemistry. The next section well provides a more detailed description of the sequence within the unit of electrochemistry.

**Key concepts and sequence.** The chemistry teachers were asked to explain which ideas they found to be the key concepts of the unit along with the sequence in which those topics should be taught. All teachers, with the exception of Roman, seemed to utilize small pieces
of knowledge to scaffold information and end with the topic of electrolytic cells. Most teachers mentioned the importance of students having a firm understanding of oxidation numbers as essential in understanding electrochemistry and the culminating idea was electrolytic cells. This is logical considering the learning cycle, which suggests students should first explore content, followed by concept invention and culminating in application (Farrell, Moog, & Spencer, 1999).

Margene had the greatest emphasis on student application of electrochemistry. Of the five lessons of her sequential unit flow, three were targeted towards learning objectives that focused on real world application for her students. Barbara also used application as her rationale for teaching the unit. Roman provided a nontraditional approach to teaching the unit. His approach seemed more from a perspective where major themes were explored surrounding the theme of energy. Roman also taught AP Biology and was the only other teacher in the study who taught both chemistry and AP Biology. Perhaps his biology background allowed him to connect concepts differently from teachers who only taught chemistry. The teachers’ responses are summarized in Table 13.

Table 13

<table>
<thead>
<tr>
<th>Instructional Sequence and Rationale for the Electrochemistry Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sequence</strong></td>
</tr>
<tr>
<td>Margene</td>
</tr>
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<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Alby</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Sarah</td>
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<tr>
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<td></td>
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<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>Benjamin</td>
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<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>---</td>
</tr>
</tbody>
</table>
| Barbara | 1-Writing half reactions  
  2-balancing half reactions  
  3-spontaneity of reactions  
  4-galvanic cells  
  5-electrolytic cells | 1-Sets up the process of redox reactions  
  2-expose students to the idea the reduction/oxidation occur simultaneously  
  3-links activity of metals to redox; sets up galvanic cells  
  4-galvanic cells are the application of electrochemistry; students are familiar with batteries  
  5-once galvanic cells are understood, electrolytic cells are much easier to understand |
| Joey | 1-identify oxidation numbers, definitions/concepts of oxidation/reduction  
  2-balancing redox reactions  
  3-voltaic cells  
  4-electrolytic cells | 1-this is the foundation for the entire unit.  
  2-combining the basic processes of reduction and oxidation to form a reaction, demonstrating conservation of charge  
  3-real-life application  
  4-real-life application |
| Roman | 1-Chemical energy to electrical energy  
  2-Chemical reactions can be driven by exchanges of electrons  
  3-electrical energy to chemical energy | 1-shows that conservation of energy applies  
  2-is the foundation for all redox  
  3-shows that it works in both directions |
| Don | 1-rules governing oxidation states  
  2-a review of the five major chemical reactions and assign oxidation suits in a chemical reaction to determine if the reaction is redox.  
  3-Half reactions now that students are determine oxidation suits and recognize what makes a chemical reaction redox reaction, the concept of half reactions can be introduced. LEO and GER are introduce, as well as the number line of charge changes.  
  4-oxidizing and reducing agents  
  5-Activity series and acid reactions including highly active versus less active metals | 1-oxidation states is used in naming and writing chemical formula early on, and allows for the first introduction of this concept. Student cannot determine whether reaction is a redox reactions unless they have a firm understanding of the rules of oxidation states.  
  2-students have hopefully master the concepts of oxidation states and what constitutes redox reaction. Now students can attend what the two half-reactions are.  
  3-students have mastered the concepts of oxidation States and what constitutes a redox reactions so now can determine what to have reactions are.  
  4-after you’re done with this step then reactions are understood.  
  5-can to penny lab demonstration to show zinc is more active than hydrogen on table J activity series  
  6-Can use the lemon battery lab to enforce activity series during open lab inquiry investigation  
  7-an apparatus to compare voltaic and electrolytic cells |
Concept map. Teachers were asked to create concept maps to show how the major concepts of the unit connected to each other. Some of the teachers were unfamiliar with how to create a concept map and as a result were not able to successfully complete this task. The following map from Barbara provided an explanation for the flow of the unit. Barbara’s map shows how she began the unit in with the definitions of the terms oxidation and reduction, followed by an explanation of what that means in terms of oxidation number (Figure 10). Included in the map was the notion that the number of electrons lost and gained were the same in redox reactions, which funneled into spontaneous reactions. There was no mention of spontaneous reactions but rather a statement that spontaneous reactions can cause electrolytic cells and additionally be used in galvanic cells.

Figure 10. Teacher TSPCK response 3.
Margene, Alby, Sarah, Benjamin and Joey had no formal training in concept mapping and basically wrote out the flow of the unit, which is addressed in a later section. For example, Sarah wrote assign oxidation numbers using the acronym LEO and GER, which is followed by half reactions which link to electrochemical cells which links back to the other ideas as well. Similarly, Alby was a little more detailed and wrote: oxidation numbers → identifying redox reactions → writing ½ reactions → balancing reactions → voltaic cells → electrolytic cells with definitions of what happens at those points.

The concept map created by Roman is shown in Figure 11. This approach took major concepts discussed at multiple points in the curriculum, conservation of mass and charge, and applied them to electrochemistry. There is evidence of curricular saliency in the teacher’s ability to connect electrochemistry to big ideas within the chemistry curriculum.

Figure 11. Teacher TSPCK response 4.
Don created a more elaborate map than Barbara and Roman. Branching from electrochemistry is the application of electrochemistry, which branches into the activity series. This is further broken down into nonspontaneous reactions represented by electrolytic cells and spontaneous reactions represented by voltaic cells. Don also pointed out the connection between the activity series to determine which elements were likely to be oxidized, which he then connected to redox reactions. Another connection stemmed from assigning oxidation states to identify redox reactions and then to writing half reactions. Don showed multiple ways in which the concepts could be connected.

The components of curricular saliency examined are shown in Table 14. All teachers indicated they understood the importance of incorporating real world/practical applications of the content into their instruction of electrochemistry. Most teachers suggested the value of spiraling previous content to the topic being taught, yet Margene, Alby, Benjamin and Don were able to provide the most detailed connections and rationale for why the topics taught prior were necessary for students to understand essential components of electrochemistry. Roman also stated the significance of the ideas of charge, mass, and energy conservation because electrochemistry was really a specific application of these larger concepts.

Table 14
Curricular Saliency

<table>
<thead>
<tr>
<th>Categories</th>
<th>Margene</th>
<th>Alby</th>
<th>Sarah</th>
<th>Benjamin</th>
<th>Barbara</th>
<th>Joey</th>
<th>Roman</th>
<th>Don</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real world/ practical applications</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>xx</td>
</tr>
<tr>
<td>Links to other science disciplines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spirals from earlier chemistry concepts</td>
<td>x</td>
<td>x</td>
<td>xxx</td>
<td>xx</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Provides rationale for why certain topics should be taught prior to electrochemistry</td>
<td>xxx</td>
<td>xxx</td>
<td>xx</td>
<td>xxx</td>
<td>xxx</td>
<td>xx</td>
<td>xx</td>
<td>xxx</td>
</tr>
<tr>
<td>Encourages higher order thinking with rigorous content</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Suggested concepts and sequence is logical and aligns with major understandings of core curriculum</td>
<td>xxx</td>
<td>xxx</td>
<td>xxx</td>
<td>xxx</td>
<td>xxx</td>
<td>xxx</td>
<td>xxx</td>
<td>xxx</td>
</tr>
<tr>
<td>Links core ideas with rational learning progressions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

In summary, the chemistry teachers felt it was important for students to learn electrochemistry because it has practical application and connects to previously learned topics. The answers provided by the teachers for the most part were generic. For instance, if the teachers were asked why it was important for students to learn an alternate topic within the curriculum, for instance acid and bases, the responses provided could have been similar (e.g., practical application, it connected previously taught topics and it was difficult for students to learn), another indication that TSPCK was lacking in electrochemistry. While many teachers talked about the importance of practical application, the only one that was mentioned by any teacher was a battery. Moreover, many teachers spoke about the difficulty of the unit. Perhaps it was also the teachers’ own difficulty in providing additional real world or practical examples that hindered students’ ability to connect the abstract concepts to practical meaning.
**Models/analogies/representations.** The TSPCK exam provided data on teachers’ use of models, analogies and representations in the unit of electrochemistry. For the analogy section, teachers were asked to state explicitly the analogies they used when teaching electrochemistry. Don wrote about cell phone batteries as analogous to a spontaneous reaction where you just turn on the switch and it works, versus a charger where you are adding electrons to reverse the chemical reactions in the battery. To teach about oxidizing and reducing agents, Don used the analogy of a secret agent giving or taking secret documents and compared them to electrons. He spoke of a lousy spy, a LEO agent, who would just give its electrons away to reduce, or a good spy, who takes the secret documents. Barbara used the analogy of a waterfall moving in one direction and just happens to understand the idea of potential difference. As seen in Figure 12, Joey used the analogy of a tug of war between the anode and cathode for electrons where the cathode is stronger.

![Figure 12. Teacher TSPCK response 5.](image)

Analogies can be useful in making the abstract nature of chemistry more familiar for students (Taber, 2003). Barbara, Joey, Roman and Don all included analogies in their instruction of this unit, which is a strength of their TSPCK. Being able to help their students compare an abstract topic to something familiar in the real world or describe the motivational function is helpful for students. Roman used the term bullies to refer to less active elements, which actually did not seem intuitive in nature. One might assume the bully was actually an element with higher electronegativity that stole electrons as opposed to the less active element as was described by Roman. As Thiele & Treagust (1994) pointed out, teachers who teach via analogies need to be aware of their flaws. It is possible that students will relate this to an idea of electronegativity and attraction for electrons, instead of potential difference. Margene, Alby, Sarah and Benjain did not incorporate analogies into their instruction of the unit. In a follow-up interview for substantive validity, these teachers were asked if they understood what the question was asking and indicated they were not aware of any analogies for the topic.

Following the section on analogies on the TSPCK exam, teachers were asked to list the models, strategies and representations they used when teaching the unit. The following sections describe the strategies teachers utilized. All teachers drew models of voltaic and electrolytic cells for their students. Barbara discussed showing the students a rusty nail to begin the unit, demonstrating that rust is synonymous with oxidation. She also set up a galvanic and electrolytic cell and used the demonstration as a model. Finally, she showed her students a picture of an oil
rig and referred back to it. OIL RIG is an acronym that stands for “Oxidation Is Losing and Reduction Is Gaining.” This was utilized to help her students remember the definition of oxidation and reduction. Roman responded with models used to teach the topic including: voltaic cell diagrams, electrolytic cell diagrams for teaching fused salts, hydrolysis of water and electroplating, an activity series chart, and reduction potential charts. Table 15 shows instances of teacher use of models, analogies or representations.

Table 15

Models, Analogies, and Representations

<table>
<thead>
<tr>
<th>Categories</th>
<th>Margene</th>
<th>Alby</th>
<th>Sarah</th>
<th>Benjamin</th>
<th>Barbara</th>
<th>Joey</th>
<th>Roman</th>
<th>Don</th>
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</thead>
<tbody>
<tr>
<td>Applicable Analogy</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Macroscopic Simulation/Animation</td>
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<td></td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-microscopic Simulation/Animation</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Macroscopic Electrolytic Cell Depiction</td>
<td>x</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atom models</td>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>Cell Potential Charts</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td>Paper and pencil diagrams of Electrochemical Cells</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td>Able to analyze strengths/limitations of models</td>
<td>xxxxxx</td>
<td>xxxxxx</td>
<td>xxx</td>
<td>xx</td>
<td>xxxxx</td>
<td>xxx</td>
<td>xxxxx</td>
<td>x</td>
</tr>
</tbody>
</table>

**Representations.** One component of the TSPCK exam provided teachers with three different representations used in the instruction of electrochemistry. Figure 13 shows typical representations most teachers have recognized. Teachers were asked how the models could be useful in teaching as well as what difficulties students would encounter.
For Representation 1, Margene, Alby and Sarah described how it could be useful because nothing was labeled, thus students could label it in order to demonstrate knowledge of the parts of the cell. Also, it was easy to read and not overwhelming. Margene and Barbara both indicated this representation might cause confusion for students because nothing was labeled. Joey thought this representation was very simple with “no frills” but might be difficult for students because it does not show movement of ions. Similarly, Alby indicated this might be difficult for students as it only shows a macroscopic view, so students would not be able to see the particulate level.

Figure 13. TSPCK exam representations.

For Representation 2, Margene, Alby and Sarah described how it could be useful because nothing was labeled, thus students could label it in order to demonstrate knowledge of the parts of the cell. Also, it was easy to read and not overwhelming. Margene and Barbara both indicated this representation might cause confusion for students because nothing was labeled. Joey thought this representation was very simple with “no frills” but might be difficult for students because it does not show movement of ions. Similarly, Alby indicated this might be difficult for students as it only shows a macroscopic view, so students would not be able to see the particulate level.
Benjamin stated this model was useful to show electrode mass changes, the salt bridge, and electron flow. Roman found the model useful for showing electron flow but confusing since they could not see a change in mass. Don thought this representation could be useful for showing the differences between the electrochemical cells, comparing the salt bridge in the galvanic to its absence in the electrolytic, but difficult since students might assume the electrons were moving toward the positive electrode. The electrons did move toward this electrode so his statements did not follow chemical sense to the researcher. Sarah and Benjamin were not able to find any reason this model might cause student difficulty.

For Representation 2, Margene thought it could be useful since it shows ions, atoms, electron flow and is still open for more notes or explanation, however, could be confusing because it does not look like a typical battery. Similar, Alby, Sarah and Don thought this representation could be useful for students to understand electrochemistry on a particulate level. Alby thought students might think gaining electrons caused the mass of the electrode to increase significantly. Benjamin stated this model was useful to show electrode mass changes, the salt bridge and electron flow, the same rationale as the previous model. Barbara thought students might struggle with this because there was a lot of information given and that could make it overwhelming. Joey explained it provided a clear magnified view of the anode and cathode, although Don thought his Regents level students might actually think the magnifications were part of the actual set up. Roman found the representation useful for showing electron flow and mass changes but confusing to students, as the actual model was not static. Sarah, Benjamin and Joey could not explain why students might find it confusing.

Representation 3, shown in Figure 14, was most confusing for the chemistry teachers.

![Diagram](image1.png)

*Figure 14. Concrete model for teaching electrochemistry (Huddle & White, 2000, p. 105).*

They had never seen the model since it is not one that typically appears in textbooks or student guides and were unsure how it represented a voltaic cell or how it could be utilized to assist student learning. Joey stated, “Honestly, I wouldn’t use it…there’s too much going on, I’m not
sure I get it…unclear.” Barbara also stated, “it’s confusing” and thought the only possible use might be to show electron flow. Benjamin and Roman also stated they would not use it because it is confusing. Margene thought the model could be tangible and manipulated by hand however found it “daunting” and went on to state “there’s lots going on” and its “not how they [the students] are used to seeing it.” Alby indicated this model could be useful for showing an alternate way to achieve neutrality other than via a salt bridge but that is confusing as there is no salt bridge. Don thought it would be a good way to discuss semi-permeable membranes. Sarah thought this model might be useful, as it seems more tangible but also thought it was confusing with unfamiliar symbols such as the marbles. Benjamin and Don thought students would have difficulty relating this model to the concepts in electrochemistry. Along similar lines, Roman thought the analogy was too abstract and the model was too ambiguous.

While models and representations may be common tools for chemistry teachers, they need to be aware of why students who are learning a concept via the representation for the first time may be confused. Teachers’ inability to find any reason a model might be inappropriate is problematic. None of the teachers had familiarity with Representation 3. If teachers had a working knowledge of the model or had utilized it in their classrooms, perhaps they would be able to say with greater certainty whether or not it was useful and the potential challenges it might pose for students.

**Teaching strategies.** As part of the TSPCK exam, teachers were asked to describe the teaching methodologies used in their classrooms. Table 16 outlines the laboratories that students of the chemistry teachers performed. Barbara had her student engage in the most hands on laboratory experiences. There exists great variation in the laboratories chosen, with little overlap between teachers. Additionally, despite all teachers stating they had their students engage in hands on activities, there seemed to be inconsistencies between the teachers’ philosophies and what they actually did in the classroom. Teachers may know or believe that students learn best through laboratories but some lacked the TSPCK to provide students opportunities to engage in hands on experiments, in general providing minimal lab exposure for this particular unit.

Table 16

<table>
<thead>
<tr>
<th>Laboratory Activities</th>
<th>Margene</th>
<th>Alby</th>
<th>Sarah</th>
<th>Benjamin</th>
<th>Barbara</th>
<th>Joey</th>
<th>Roman</th>
<th>Don</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investigating oxidation states</td>
<td></td>
<td>x</td>
<td></td>
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<td></td>
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<tr>
<td>Electrolysis</td>
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<tr>
<td>Silver Mirror</td>
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<td></td>
</tr>
<tr>
<td>Penny Single Replacement Reaction</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
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<td></td>
<td>x</td>
</tr>
<tr>
<td>Creation of an Activity Series</td>
<td>x</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Lemon Battery</td>
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</tr>
</tbody>
</table>

In addition to labs, some teachers showed demonstrations relevant to the unit. Table 17 lists the demonstrations and the teachers who indicated they utilized them in their lessons. Similar to the laboratory activities, there was variation amongst the demonstrations. The only demonstration that was consistent for three teachers was to show a voltaic cell (Margene, Alby and Sarah).
Table 17

Teacher Demonstrations

<table>
<thead>
<tr>
<th>Demonstrations</th>
<th>Margene</th>
<th>Alby</th>
<th>Sarah</th>
<th>Benjamin</th>
<th>Babara</th>
<th>Joey</th>
<th>Roman</th>
<th>Don</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nail Rusting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel Wool and CuSO₄</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
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<tr>
<td>Single Replacement Reaction</td>
<td>x</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Voltai Cell</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Electrolytic Cell</td>
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<td></td>
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<td></td>
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<td>x</td>
<td></td>
</tr>
</tbody>
</table>

Teachers were asked to describe the conceptual learning strategies or activities they utilized when teaching electrochemistry. Margene had her students pretend they were parts of a battery and move to different zones of the classroom via “paths” to represent the actions of the battery part. In addition, she asked her students to look at a video of the inside of a battery and relate it to their own diagrams to make the connection between the macroscopic and sub-microscopic. Finally, Margene also had her students create their own metal activity series. Alby used virtual simulations to show what was taking place at the atomic level as well as to help connect half reactions to the half-cells. Sarah used demonstrations of redox reactions, labs with redox reactions (specifically the reaction of the core of a penny with acid), and diagrams and simulations of both galvanic electrolytic cells. Sarah had her students label diagrams, practice writing half-reactions from complete redox reactions, practice in the lab setting by performing a redox reaction, and engage in group practice using the think-pair-share technique and animations. Benjamin left this response blank. Barbara described a Redox Fun Lab, which was used to plate copper onto a nail and had students apply those skills to complete a silver mirror lab where they reduced silver ions with dextrose to make the inside of a glass bottle appear as a silver mirror. She also set up an electrolytic cell to show electrolysis and let it run throughout the period so students could diagram and explain what they observed. Joey had his students complete a reactivity of metals lab and plenty of practice problems and videos, although the videos were not for the purpose of flipped learning.

Roman discussed the use of the predict-observe-explain (POE) model to teach the following: steel wool in CuSO₄, Hoffman Volt, Wet Cell and a CuSO₄ and Al drawing activity. The POE model required students to make predictions prior to observing the reaction, observe, and then explain the demonstration. Roman also had his students analyze cells to determine voltage and spontaneity. Roman was the only teacher who described the POE model. This method fostered more student construction of knowledge as opposed to traditional demonstrations where the teacher staged and guided the questioning.

Don stated the best example he used for a conceptual learning strategy was his battery challenge lab, where students were given the challenge of building the best battery from various metals and fruits. They constructed anything they wanted within reason but had to justify how their actions made the battery better or worse. Additionally, students were asked to explain how the chemicals in the lemon battery related to the chemicals in the car battery. This was a real-world application of electrochemistry and one in which students had to use their background knowledge, make inferences, make predictions, and apply personalization by creating their own representations of a voltaic cell.
The summation of particular pedagogical strategies implemented during the unit described above were tabulated in Table 18. Roman showed the greatest variety of instructional strategies. Half of the teachers in the study used flipped instruction while the rest used more traditional methods of instruction. All teachers incorporated diagram drawings, acronyms, cooperative learning, whole class instruction and test preparation during instruction of voltaic and electrolytic cells. Only one teacher, Roman, assessed prior knowledge and for all teachers electrolytic cell laboratories were not present and electrolytic demonstrations were utilized by Barbara only.

Table 18
Various Methodologies for Teaching Electrochemistry

<table>
<thead>
<tr>
<th>Instructional Strategy</th>
<th>Margene</th>
<th>Alby</th>
<th>Sarah</th>
<th>Benjamin</th>
<th>Barbara</th>
<th>Joey</th>
<th>Roman</th>
<th>Don</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assess prior knowledge</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Lecture</td>
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<tr>
<td>Flipped video</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td></td>
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<td>Whole class explanation</td>
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<td>x</td>
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<td>Textbook reading</td>
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<tr>
<td>Reactivity of metals demonstration</td>
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<td></td>
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<td>Reactivity of metals demonstration</td>
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<td>Reactivity of metals laboratory</td>
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<tr>
<td>Reactivity of metals demonstration</td>
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<td>x</td>
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<td>Electrolytic cell laboratory</td>
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<td>Electrolytic cell demonstration</td>
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<td>Analogies</td>
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<td></td>
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<tr>
<td>Animation/video</td>
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<td>Virtual simulation</td>
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<td>White board drawings/modeling</td>
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<td>Cooperative learning</td>
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<td>x</td>
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<td>x</td>
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<tr>
<td>Practice problems via worksheets</td>
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<tr>
<td>Test/final exam preparation</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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</tr>
</tbody>
</table>

- Indicates that the teacher has in the past but not for the students involved in this study.

Authentic responses to student answers. The teachers were asked to respond to authentic student responses on the TSPCK exam. The first question asked how best to respond to a learner who wrote on the test: “Electrons flow through the salt bridge to keep the galvanic cell neutral.” Barbara responded by stating that electrons are not found in the ionic solutions and electron flow is due to potential differences between the metals. Margene said that she would respond by asking the student what the purpose of the wire was, or questioning how can you harvest electricity or by asking if an electron is a salt. Alby would tell the student that electrons travel to the wire whereas ions travel through the salt bridge and the flow of electrons creates electrical energy, whereas ions use the salt bridge to maintain neutrality. Sarah stated she would explain,
“electrons flow to the wire, the ions through the salt bridge to prevent polarization.” Benjamin said he would go back to what happens to electrons during oxidation and reduction and ask the students where the electrons go in the cell. He would try to emphasize that the change and loss of ions alters polarity in the cell and ions go through the bridge to maintain proper charge. He indicated he would follow up with an animation that shows the process for students to observe on a sub-microscopic level. Joey explained the electrons flow to the wire and ions flow through the salt bridge to keep the half-cells electrically neutral. Don would ask the student, “Where are the electrons actually going in the electrodes?” to help the students see the electrons are coming out of the oxidized metal, going through the wire to the reduce metal. He would also ask, “What charged particles do you find in a salt bridge?”

Margene provided more questions to try to lead the students to come to a conclusion about the particles traveling through the salt bridge. Roman used a similar strategy to Margene, where he would provide the students with more questions to try to guide students’ understanding to the correct idea. For the student he listed three questions he would ask in response to the question: 1) Why do you think it is happening? 2) Can electrons go through the salt bridge? 3) Where is the load getting its power from?

The second question prompted the teachers to respond to a student who asks, “Why is it true that in both electrolytic and galvanic cells, oxidation always occurs at the anode and reduction always occurs at the cathode?” Margene explained the anode and cathode are “names given to the metal plates based on the reaction that takes place in their half-cell.” Alby explained oxidation always occurs at the anode and therefore electrons flow to the cathode side, and this occurs spontaneously in galvanic cells and is the reason we need a battery in an electrolytic cell – so we can force the nonspontaneous reaction to occur. Sarah stated she would explain the anode always loses mass when oxidation is occurring since ions are becoming atoms, however, this was inaccurate since at the anode atoms lose electrons and become ions. Benjamin said he would explain that in a voltaic cell, the anode is always the more reactive metal that is losing electrons, and then he would describe how in electrolytic cells “the anode is always positive, it attracts the negative ions which loses electrons.” Barbara would respond that the definition of anode and cathode do not change with the types of cells, rather the charge of the electrode changes. For this question, Joey would tell the student that both cells are applications of redox reactions, which utilize both oxidation and reduction and that the anode is set as the location for oxidation and the cathode is set as the location for reduction. Depending the level of the student, he would bring in the concept of reduction potentials. Roman again provided a series of questions to guide the student. First, he would ask why should it be otherwise? Second, he would ask what do “anode” and “cathode” mean? Lastly, he would ask why are the anode and cathode charges the opposite? Don would ask the students to recall the acronym RED CAT and the important concept to understand is the charge of the electrodes change with the type of cell used – electrolytic vs. voltaic.

The chemistry teachers were asked how they would guide students to get the correct answer when provided the student responses in Figure 15. Students were asked to write an oxidation half-reaction for the following: 2NaCl → Cl₂ + 2Na.
The students were asked to write a half oxidation reaction for the equation above. The following responses from students were obtained:

<table>
<thead>
<tr>
<th>Student Response 1</th>
<th>Student Response 2</th>
<th>Student Response 3</th>
<th>Student Response 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Cl}^2+ - 2\text{e}^- \rightarrow 2\text{Cl}^- )</td>
<td>( \text{Na}^+ + \text{e}^- \rightarrow \text{Na} )</td>
<td>( 2\text{Cl}^- = \text{Cl}^2+ + 2\text{e}^- )</td>
<td>( 2\text{Na}^- - 2\text{e}^- \rightarrow 2\text{Na} )</td>
</tr>
</tbody>
</table>

*Figure 15. TSPCK test item (adapted from Rollnick & Mavhunga, 2014).*

The oxidation state of each sodium ion changes from positive one to zero, indicating electrons have been gained, thus the sodium ions are reduced. The chloride ions lose electrons in the form of elemental chlorine. Since oxidation is the loss of electrons, the chlorine ions are being oxidized; the oxidation state changes from -1 to 0 and electrons are lost. The following section will provide the responses of the chemistry teachers in each of the given student responses for the oxidation half-reaction.

**Student response 1.** Student one identified that chlorine is being oxidized, however, incorrectly reversed reactants and the products. Student one’s oxidation half-reaction showed chlorine atoms gaining electrons to become chloride ions. For student one, Barbara wrote that she would remind the student of the definition of oxidation and reduction and ask him where the electrons are located in oxidation and why is gaining “reduction.” Margene stated she would use the given equation to emphasize the starting reactants are a sodium ion and a chloride ion, state that those must stay reactants, and ask students to consider that the charges are being reduced. Alby responded that each Cl is “gaining one electron not two.” Sarah explained, “Oxidation
means electrons are lost. Electrons are always written as a product. Cl starts as Cl ions and gains electrons to become a Cl\(_2\) atom.” Benjamin would ask if the reaction shows loss or gain of electrons after having the student clarify what happens to electrons during oxidation and reduction. Joey would review the definition of oxidation and reduction and assign oxidation numbers to balance equation in the diagram. For this student, Roman would ask whether Cl\(_2\) is being oxidized or reduced. He would point out that Cl\(_2\) is on the product side of the reaction and that they put the Cl\(_2\) on the reactant side of the half reaction. Additionally, he would ask what LEO and GER mean and is this reaction losing again electrons. Finally, he would ask the student what it means to become more positive or more negative.

Alby possessed his own misconceptions regarding the topic because two electrons are needed to balance that equation and chlorine does not exist as an atom but rather a diatomic molecule. It is unclear what he is referring to or how that would assist the learner. Sarah also showed a lack content knowledge here - “Cl\(_2\) (atoms)” is a molecule and although electrons can be written as a product via addition, a correct oxidation half reaction can be written showing subtraction of the electrons from the reactants. Don fell into the trap of asking whether this reaction lost or gained electrons without specifying that the student was just looking at one half of the process occurring. Additionally, the reaction does not lose or gain electrons or other species within the cell. Sometimes in an effort to become more colloquial to the students the teacher may actually introduce a misconception.

**Student response 2.** Student two incorrectly wrote an oxidation half-reaction that showed a sodium atom losing an electron to become a sodium ion. In the reaction that students are supposed to describe, sodium is being reduced so should not have been written by the student as a half oxidation reaction. For this reaction, Margene stated she would indicate something similar to what she did to student one – that the reactants in the original reactions must remain reactants. Alby explained electrons are negative so gaining an electron will lead to reduction in oxidation state. Benjamin would ask if the reaction in the problems started with sodium atoms or sodium ions after having the students labeled oxidation states. Barbara stated that first you should remind them that balanced half reactions show balance of charge followed by a similar response to student one. Joey would review the definition of oxidation and calculate total charge of reactants and products. For this student, Roman would ask, “What happens when sodium gains an electron?” Don would review what happens when you add an electron to a particle that is neutral, in this case the sodium atom. He would ask the students to go back and show him what the oxidation states are in the initial reaction and ask if the sodium is on the product or the reactant side. He would again discuss oxidation and reduction in terms of LEO and GER. Don showed a heavy reliance on the students’ understanding of acronyms to teach the topic, frequently mentioning that he refocuses the students’ attention back to LEO and GER.

**Student response 3.** The response provided by student three showed chloride ions losing electrons to become chlorine atoms. The equation is showing the correct oxidation except that instead of providing a yield sign the student provides an equal sign. For student 3, Barbara stated she would explain to the student an equal sign is not the same as an arrow and that an arrow means “produces.” For this student, Margene indicated she would ask the student to show the direction of the reaction and request that the student explain whether the reaction was reversible. Alby indicated in the reaction you are producing a product, which is indicated by the “\(\rightarrow\)” sign, not an equal sign which is used in math to represent a mathematical relationship. Sarah indicated that chemical reactions use arrows to separate reactants from products. Benjamin would ask if
the Cl– is still present and explain that the “→” must be used to show a change, not the “=” to show that both sides are equal except for the number of molecules and charge. Joey would say this is not a reaction to equilibrium and would review the definition of equilibrium. Roman would ask the students what is the purpose of the equal sign. Sarah indicated she would approach the student from more of a symbolic viewpoint. Benjamin’s statement about the number of molecules and charge not being equal when an equal sign is present does not seem to make sense chemically. Perhaps, he was indicating only the mass is equal with an equal sign.

**Student response 4.** Student 4 showed sodium ions losing two electrons to become sodium atoms. The error here is that the sodium is not the ion that is being oxidized, chlorine ions in the reaction are the ions that are losing electrons to become oxidized. For student 4, Barbara would explain that balance of charge is not shown as well why the electrons are written on one side of the arrow instead of the other and why a “gain” is reduction. Margene would tell the students that oxidation means the charge is increasing and reduction means the charge is decreasing, and then ask the students to assess what had happened in the half reaction. Alby stated removing an electron would lead to a product that has a lower oxidation state. For this question, Sarah wrote that she would tell the student oxidation means loss of electrons, therefore, should be written as a product and that “we always add in reactions not subtract.” Benjamin would ask whether the sodium ion was gaining or losing electrons, and state electrons are negative and that the minus sign is not needed because electrons are gained not lost. Joey would review the definition of oxidation and have the student write a half-reaction. Roman would respond by asking, “Why did you include the minus sign?” This would be followed by, “What would happen if you remove the electron from the sodium ion?” He would also ask the student, “What happens when you take away two or more negative electrons from an ion that is already missing one?” He would show a model of the sodium atom with its 10 electrons and 11 protons asking what the charge was, then would remove two more electrons and ask the student what the new charge was.

Alby’s response was that removing an electron leads to a product with a lower oxidation state. This is an incorrect response, as removing an electron would lead to an increase in oxidation number. Alby struggled with this aspect of the TSPCK exam indicating a lower level of content knowledge in this domain. As was mentioned above, Sarah’s and Benjamin’s responses did not show an understanding of the ability to subtract electrons to balance an equation. Joey’s approach centered around reviewing related prior concepts as opposed to targeting the specific error. The Regents exam did not typically show reactions with electron being subtracted.

Teachers Sarah and Benjamin only seemed to be aware of the type and style of questions provided on the Regents exam. This is problematic. When content outside of the scope of the Regents exam was being assessed, some teachers could not recall it or were unaware of how to teach learners to find the correct chemical explanation. If teachers are not required to teach high level content, they often forget or lose their ability to teach anything beyond the scope of exactly what is being tested.

**Assessment.** The following section outlines the reported strategies used to assess student learning of electrochemistry – both formative and summative. Margene provided her students with a significant amount of short answer questions throughout the unit, labs and lab discussion questions, questions within flipped videos, visual activity worksheet responses, classroom clickers and final exam multiple-choice and constructed response questions to prepare the students for the end of year Regents exam. Alby had his students come up with their own actual cells and describe what was occurring in the cells as a form of assessment. He also had them
visualize the flow of electrons having them fill out diagrams and manipulate virtual simulations to demonstrate understanding of complete redox reactions. Sarah assessed her students via labs, quizzes, practice problems, and a unit exam. Benjamin provided assessment in the form of do nows, quizzes, exams, classwork monitoring, Kahoots (an online assessment where students answer questions via an electronic device), and EDpuzzle (where he is able to embed questions into his flipped videos). Barbara assigned homework every night to practice the content and homework was reviewed in class. There was a quiz given on writing half reactions, identifying oxidation and reduction agents and balancing redox reactions. Additionally, Barbara quizzed on galvanic cells with identification of the anode and the cathode, stating direction of electron flow, balancing reactions, and determining voltage. There was a summative exam comprised of old Regents type multiple-choice questions and constructed response questions and lab reports were required for two labs. Joey provided quizzes throughout the unit, homework assignments, and a summative exam. Roman incorporated a significant amount of questioning into his lessons to informally assess the students. Roman also used white boarding followed by student explanations to justify their models, diagrams, etc. Students were also required to answer questions during their flipped videos and were formatively assessed via quizzes and exams. Don assessed his students by giving nightly homework assignments that were collected and graded, which he used to tweak the next day’s lessons. If students did not understand the concept of oxidation numbers, the next period would be spent reviewing or re-teaching that concept before proceeding. Don offered two types of quizzes, Castle Learning and in-class quizzes. Castle Learning quizzes have the same types of questions as the in-class quizzes to compel students to learn the ideas or look them up. An exam is given at the end of the unit with bonus questions about a given concept. Students have the ability to take a pass on the electrochemistry questions but then they do not get to count the bonus questions if they utilize this option.

When comparing the assessments of the teachers in the study, all teachers incorporated homework and quizzes and some type of summative test. Some of the teachers incorporated a lab quiz or lab assessment. The degree of formative assessment varied drastically from teacher to teacher. Barbara and Joey utilized the least amount of formative assessment mainly by relying upon students’ performance on paper and pencil tasks to assess understanding of chemistry concepts, however both taught honors and AP Chemistry students. Roman provided students the opportunity to draw and explain what they thought was occurring in the voltaic and electrolytic cells. Roman provided the most opportunities for formative assessment prior to the summative assessment. The assessment style of Don allowed students to not complete some of the electrochemistry exam questions they did not understand, and included them as bonus material. Students may be unlikely to prepare for material that they know they can omit or pass on with no penalty. Since electrochemistry is assessed on the Regents Exam, it is unclear why the teacher chose this method.

**Limitations of TSPCK exam.** One limitation of the TSPCK exam was that the teachers completed the exam over the summer following the unit of instruction. The information was not fresh in the subjects’ minds. It is possible for them to have forgotten some information they may have remembered if the TSPCK exam were administered immediately after they taught the unit. However, the exam was designed in such a way to minimize these limitations. For instance, when asking teachers to explain what they found difficult to teach, or what student misconceptions were for the unit, there were no sources to draw upon but their own knowledge
and memory, without access to outside materials or sources, so in that respect the self-reporting nature of the exam minimized potential skew.

### 4.7 Interview Tasks

This section describes the interview tasks each participant completed. The first task asked teachers to describe the definitions of oxidation and reduction used in their classroom as well as difficulties they pose to student learning. Secondly, teachers were asked to describe a demonstration lesson of choice and include what prior knowledge the teacher would need to know. Next, teachers were asked to have their students shrink down and describe what they think their students would see occurring on a sub-microscopic level as a voltaic cell operates. Afterwards, teachers were asked a series of questions regarding authentic student questions during a demonstration lesson and finally how they would assist students in answering a question regarding an electrolytic cell. To assess the TSPCK of each teacher, the interviews were coded. The next section will describe the code development and process. This will be followed by a detailed description of the teachers’ responses to each of the interview tasks.

**Coding.** The interview tasks were coded to identify teacher knowledge and beliefs about redox and electrochemistry. The coding utilized was similar to that used by Van Driel et al. (1998) and validated by Mavhunga (2012) as an effective means of transcribing teacher knowledge and beliefs. These codes are summarized in Table 19. The use of these codes allowed preliminary provisional coding by the researcher (Creswell, 2012; Miles & Huberman, 1994), that is, anticipated categories were elicited from previous research yet revised and modified in response to the data. These codes allowed for immediate identification of teacher beliefs and behaviors that applied to various constructs associated with chemistry teacher PCK. The TSPCK themes that emerged were curricular saliency, student learning challenges, and teaching methodology. The TSPCK exams were coded in cooperation with members of the science education faculty in order to agree on the coding scheme. Differences in values were discussed for clarification so that inter-rater reliability was established.
<table>
<thead>
<tr>
<th>TSPCK Themes</th>
<th>Axial Codes</th>
<th>Axial Code Meanings</th>
<th>Open Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Curricular Saliency</strong></td>
<td>Real life application</td>
<td>Teacher mentions an application or connection to real life phenomena</td>
<td>Unit pacing</td>
</tr>
<tr>
<td></td>
<td>Instructional sequence and pacing</td>
<td>Teacher lesson flow or sequence for the unit or units prior as well as the amount of time allotted for each lesson/unit</td>
<td>Unit flow</td>
</tr>
<tr>
<td></td>
<td>Key concepts and connections</td>
<td>Gate keeping concepts mentioned such definitions of oxidation and reduction or spiraled curriculum to connect concepts taught previously</td>
<td>Regents Exam</td>
</tr>
<tr>
<td></td>
<td>Timing on unit vs. final assessment</td>
<td>Teacher mentions Regents or AP Exam as a rationale for the length as a rationale for the way the curriculum is being taught</td>
<td>Planning</td>
</tr>
<tr>
<td></td>
<td>preparation</td>
<td></td>
<td>Lesson flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spiral</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Timing</td>
</tr>
<tr>
<td><strong>Obstacles to Student Learning</strong></td>
<td>Difficult concepts and misconceptions</td>
<td>This deals with challenging ideas or false ideas about a topic students find difficult</td>
<td>Student difficulty</td>
</tr>
<tr>
<td></td>
<td>Context</td>
<td>This deals with Regents or AP meaning standard or college level students as a indicator of the level of students be taught</td>
<td>Regents Exam</td>
</tr>
<tr>
<td></td>
<td>Sub-microscopic understanding</td>
<td>This deals with the particle nature of chemistry, particularly atoms and ions</td>
<td>Difficult to learn</td>
</tr>
<tr>
<td></td>
<td>Comprehension of student learning</td>
<td>The teacher is aware of how students will answer questions or arrive at conclusions</td>
<td>Misconceptions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Alternate conceptions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sub-microscopic understanding</td>
</tr>
<tr>
<td><strong>Teaching Strategies</strong></td>
<td>Labs and activities</td>
<td>Teacher specifically mentions a particular lab or activity students engage in to learn the material</td>
<td>Macroscopic/Sub-microscopic/Symbolic Representations</td>
</tr>
<tr>
<td></td>
<td>Acronyms</td>
<td>Acronym used to teach such as LEO, GER, OILRIG, ANOX, RED-CAT</td>
<td>POGIL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>POE (Predict, Observe, Explain)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Literacy</td>
</tr>
</tbody>
</table>
### How oxidation and reduction were defined

During the TSPCK exam, teachers mentioned that students struggle with the definition of oxidation and reduction. Since definition confusion was an area of difficulty, during the interview phase teachers were asked about their approach to teaching oxidation and reduction to their students. Specifically they were asked whether they taught the following four definitions: 1) oxidation is the loss of electrons and reduction is the gain of electrons, 2) oxidation is an increase in oxidation number and reduction is a decrease in oxidation number, 3) oxidation is the gain of oxygen and reduction is the loss of oxygen, and 4) oxidation is the loss of hydrogen and reduction is the gain of hydrogen. The results provided by each teacher are provided in Table 20.

#### Table 20

**Definitions of Oxidation and Reduction Taught**

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Oxidation is loss of electrons and reduction is gain of electrons</th>
<th>Oxidation is an increase in oxidation number and reduction is a decrease in oxidation number.</th>
<th>Oxidation is gain of oxygen and reduction is loss of oxygen.</th>
<th>Oxidation is a loss of hydrogen. Reduction is a gain of hydrogen.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Margene</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alby</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sarah</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benjamin</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barbara</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Roman</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Don</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All teachers stressed that oxidation is the loss of electrons and reduction is the gain of electrons as well as the notions that oxidation is an increase in oxidation number and reduction is a decrease in oxidation number. Only one teacher, Barbara described all the definitions of oxidation and reduction.
oxidation and reduction. Barbara, gave a historical perspective of oxidation as the addition of oxygen when she said:

Well, it's the, you know, oxidation's the loss of electrons. Why? Why did it come about? Oxygen's very attracted to electrons. It's able to pull it away. So, I do get into that... I get into the dot structure of oxygen. You know, it's got two lone pairs... I tell them oxidation came first – they didn't understand what was happening. They knew that metals were combining with oxygen in the air and so it was called oxidation, but they didn't know that there was such a thing as an electron. And then reduction came about and that's how I then get into the idea of look at what happens to the oxidation state when something is reduced.

Barbara provided evidence of TSPCK in her ability to make connections in the topic as well as emphasize the historical component to address the student difficulty along with sound curricular saliency.

**Demonstrations.** During the interview each teacher was asked to describe a demonstration she would do if called into a job interview. Most of the teachers chose something in the realm of voltaic cells and only two teachers chose a demonstration related to electrolytic cells. Alby said he would have the class electroplate keys. Barbara would show the electrolysis of copper (II) chloride solution. Table 21 lists the demonstrations chosen by each teacher as well as the activities and labs each teacher mentioned.
Table 21  
Comparison of Teacher Demonstrations with Voltaic and Electrolytic Cells

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Demonstration Lesson Demo of Choice</th>
<th>Voltaic Cell Demonstration/Activities</th>
<th>Electrolytic Cell Demonstrations</th>
<th>Electrolytic Cell Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Margene</td>
<td>Single Replacement reaction</td>
<td>-Virtual Lab</td>
<td>-None</td>
<td>None</td>
</tr>
<tr>
<td>Alby</td>
<td>Electroplate keys</td>
<td>-Voltaic Cell Demo -Virtual Voltaic Lab</td>
<td>None</td>
<td>Electroplating (every other year)</td>
</tr>
<tr>
<td>Sarah</td>
<td>Potato clock</td>
<td>Daniel Cell Demonstration</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Benjamin</td>
<td>Voltaic Cell</td>
<td>-Voltaic Cell Animation</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Barbara</td>
<td>Electrolysis of Copper (II) Chloride solution</td>
<td>Mini Voltaic Cell Lab -Silver mirror lab</td>
<td>-U-Tube Electrolysis of Copper (II) Chloride -Hoffman Apparatus -electrolysis of water</td>
<td>None</td>
</tr>
<tr>
<td>Joey</td>
<td>Reactivity of metals-Zn, Cu, Mg and acid or metal solutions</td>
<td>-Voltaic cell simulation</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Roman</td>
<td>Zinc and HCl and Fe and Copper (II) sulfates</td>
<td>-Construct a wet cell</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Don</td>
<td>Voltaic Cell (Zinc and Copper)</td>
<td>-Lemon Battery Lab</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

Observing the responses it was evident few students were engaging in activities related to electrochemistry. Only one teacher year-to-year showed a demonstration related to electrolytic cells. While most teachers discussed the application to one or more real life examples, there was a clear lack of student hands-on application of the topic. Barbara talked about her experience with the electrolysis demonstration:

I love that the kids can connect what they talk about on the board and they can see it for real. It's tangible. They can see the copper depositing. They can see the chlorine. They can see the bubbled gas. They can actually – if they come up close enough – they can smell the chlorine gas, so they can actually see that what I'm talking about on the board and what we're discussing is happening.
**Constraints with standardized testing and teaching electrochemistry.** When surveyed, teachers all stated that they promoted hands on activities in their classrooms but this was not happening in the topic of electrochemistry. Teachers suggested some reasons for their lack of attention in this area due to the following factors. First, they were frustrated with the lack of time since this was usually the end or penultimate unit. They believed time would be better spent reviewing for the final assessment. The amount of pressure to have students perform well on this high stakes exam was evident among most teachers. The theme of final assessment impacting the teaching and learning of this unit was brought up multiple times throughout the interviews.

When discussing real world applications, Margene mentioned electroplating a key or a coin since “those are usually the ones that are on the exam or key.” Additionally, when showing her students a demonstration of a single replacement reaction, her rationale for the metal she chose was: “I usually do the zinc and copper since it’s the most common on an exam.” Sarah lamented the unfortunate constraints of the high stakes final exam questions implication in terms of what gets taught during the redox and electrochemistry unit:

And another piece is that it’s not – it’s not really asked so much on the test. I mean there’s maybe, I don’t know, a handful, not even a handful of questions on them… I mean even this last exam; the redox question was not like anything they’ve ever seen. So I don’t know – I'm going to say the biggest factor is probably time, the amount of time they want to spend on the unit to the amount of time that they need to review the big stuff that’s going to be the majority of the test, which is unfortunately sad, but true.

Alby also discussed how his students were lower functioning and thus he could not add any extra information that was not assessed into his lessons:

Most of my students are lower level, so I try to keep it basic. I don't teach like the Regents anymore. I try to – I think it's not really testable. There's a couple things but for the most part, if it's not going to be tested I don't give them extra finishing 'cause they have a tough time as it is getting through what's required.

Sarah shared the similar comments on final assessment:

I mean it’s hard to judge what they truly understand about, you know the operating – the cell, because in all honesty the Regents doesn’t ask much about it, so in the Regents level course we’re going to tell them the facts about it and this is what you have to know about it and, you know, in hopes that they understand it as we go through it. But typically, this unit doesn’t have much time towards the end of the year to really sit down and focus on what is really happening. Even on the Regents level we don’t go into voltage and all that, so almost like – it’s almost like disconnected, so it doesn’t have a connection.

Sarah showed how the strain of the final assessment, the Regents exam affected her TSPCK. She based the extent of her instruction on exactly what the students would be assessed.

**Predicted student responses and remediation strategies.** To assess how teachers would teach students in the moment, a further attempt to understand their TSPCK in electrochemistry, they were provided with an electrochemistry exam question. Figure 16 below was taken from the August 2015 NYS Regents Assessment (NYSED, 2017b). The teachers were all asked if they
thought the question was fair and what answer choice they thought they students would pick. They then proposed strategies for helping their students arrive at the correct answer. The question was piloted on three separate teachers and all teachers seemed to have difficulty or experienced confusion when answering the question. Since the teachers were confused the question was chosen to see how teachers would help students arrive at the correct answer in preparing for an exam.

![Diagram of an incomplete electrochemical cell]

**Figure 16.** Exam question taken from final assessment.

Most teachers mentioned students would experience difficulty in answering this question because it was not often asked on the final exam in this format. This further suggests that teachers are too often teaching to the test in the domain of electrochemistry. The fix-up strategies, or means by which teachers help students correct their misconceptions and come to chemically correct understandings, are shown in Table 22. The responses were not often sub-microscopic but more simple macroscopic ways of helping students arrive at a correct answer.
### Table 22
*Student Predicted Student Responses and Fix-Up Strategies*

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Student predicted answer</th>
<th>Why do you think students will pick their answer?</th>
<th>Fix-up strategies to differentiate voltaic and electrolytic cells</th>
</tr>
</thead>
</table>
| Margene | Voltmeter                | Most Regents questions are voltaic and this would correspond to a voltaic cell or more common response | - Look at reactivity of metals chart  
- Determine the motive or goal of the experiment |
| Alby    | Voltmeter                | It’s not the typical question format students see for electrolytic cells | - Determine whose losing and gaining electrons  
- Spontaneous or not  
- Battery present or not |
| Sarah   | Voltmeter                | More time spent in class on voltaic cells | - 1 solution vs 2  
- Salt bridge  
- Diagram comparison |
| Benjamin| Battery                  | They think it’s a voltaic cell | - Are you producing a substance  
- Spontaneous or non-spontaneous |
| Barbara | Battery                  | They say it’s an electrochemical cell and typically the Regents says electrochemical for voltaic cells and electrolytic for electrolytic cells | - Refer back to demonstration done in class  
- Salt bridge  
- Separate or one container  
- Power source or no power source |
| Joey    | Voltmeter or each other  | Electrochemical is typically used on Regents exams for voltaic cells | - Look for salt bridge or porous barrier  
- Look for 2 solutions  
- Battery or power source vs. no battery |
| Roman   | Battery                  | Confuse it with the voltaic cell | One solution vs two solutions |
| Don     | Battery or voltmeter     | They may confuse this with lemon battery lab | - Electrolytic cells never have a salt bridge |

Teachers would benefit from professional development aimed at teaching methodologies for teaching electrochemistry. More tools are needed on order to help students learn the content. It seemed as though the chemistry teachers were lacking in their ability to transform this content into a form of knowledge that improved student learning. More explicit TSPCK training in electrochemistry would mitigate the problem. Teachers’ ability to identify how students respond indicated that the teacher had TSPCK in knowing what misconceptions students may have in the identification of whether the cell was electrolytic or voltaic. Teachers should have been able to provide multiple strategies to assist their students to differentiating the voltaic and electrolytic cells considering these are the only two types of cells discussed in Regents curriculum. All
teachers should have known that electrolytic cells can occur in one solution and voltaic cells require a salt bridge and do not require a power source, as those are all covered within the scope of the curriculum, however, only Barbara and Joey did so successfully. Teachers’ inability to provide more detailed rationales of the different types of cells showed a lack of TSPCK.

**Shrinking task.** Teachers were asked to think about how their students would explain what is happening in a voltaic cell on a particulate level. For this shrinking task, teachers were provided with a card with a picture (Figure 17). They were asked to predict how they thought their students would envision swimming around inside the beakers of a classic Daniel cell and how students would describe what they would see on a particulate level. Teachers were prompted to discuss what they thought their students would see in terms of atoms, ions, electron movement, and quantity. None of the teachers in the study wanted to provide students with the answers. All wanted to guide the students to the correct answer and allow the students to take risks. Benjamin commented on his feeling “dirty” if he just gives the students the answer:

You know what I mean, to try and – you know, I don't want to just tell them the answer, 'cause I can't stand just telling them the – I feel like I'm – I don't know. I just – just feel dirty after that, you know? It's like I'm not doing anything. It's just lazy.

![Figure 17. Shrinking task.](image)

All teachers commented on the difficulty of getting students to understand chemistry on a particulate level. One of the reasons chemistry is so challenging for students is its three-fold nature: macroscopic, sub-microscopic and symbolic. Considering this, it is interesting that Sarah and Barbara did not incorporate this idea into the instruction. Barbara stated:

That's not kind of how I approach the lesson… I don't know if they really understand, particularly the weaker ones – they may think they understand, but I think they have issues with the vocabulary for particles. What's an ion? What's an atom? You know, they don't know and they use those terms very loosely in understanding – not really grasping what they definitely are.

Sarah also did not teach from a sub-microscopic viewpoint. She commented:
I think they would have trouble even recognizing what would be in the beaker. I'm not really sure they would be able to articulate that. I could explain it to them and try to talk to them about how the ions dissociate in a solution, and they would be separated and you’d see ions either going to the anode or the cathode. I'm not sure what they would say. I really have never asked them to put themselves in the beaker.

Benjamin also described his thoughts about asking students to *shrink down*. He said:

> It’s a losing battle, to have them shrink down, just because they an atom is so tiny that I don't think they can shrink themselves down that small... I think at this level, to try and get them to comprehend – I mean, we're not talking about, you know, college-level chemistry where – you know, where they're gonna grow up and become electrochemists, you know? They're like tenth and eleventh graders… So I feel like you gotta pick your battles.

This comment provides particularly valuable insight into the teacher’s approach to teaching his class. The final assessment is of extreme importance and he did not feel his students would go on to study chemistry in the future. Implications of such a quote are that the TSPCK of the subject is limited by the length of the curriculum and the emphasis on test preparation as a means to drive instruction. Moreover, this comment speaks to a low level of TSPCK in this area in that the teacher assumed the students would not be able to understand the sub-microscopic nature. The teacher showed a deficit view of students’ potential to pursue a STEM career. This is not the type of attitude evident in most of the chemistry teachers but is worth noting.

Alby used virtual labs since his students often had difficulty understanding electrochemistry on a sub-microscopic level. When asked if he thought students had a hard time understanding what was happening on the particulate level if they were to *shrink down*, he stated:

> No, not really. I mean the problem is they ask the same questions over and over and there's only so many questions they ask on the concept and I think really kids get it. It's the only problem I had I said this year and every year I have a problem of, of something in, in detail and only the kids that, that really, truly got it or the kids that have a good memory can spit it back out.

Perhaps his use of the virtual lab helped the students visualize and understand what was happening within a solution on a sub-microscopic level at the anode where atoms lose electrons entered the solution as ions and at the cathode where ions gained electrons and became atoms.

In summary, most teachers assumed that students would experience difficulty if they were to try to teach chemistry at particulate level, so no attempt was made to expose the students to it. It would appear difficult for students to be able to understand the threefold nature of chemistry considering they are missing one corner of Johnstone’s triangle (Johnstone, 1997). Chemistry teachers need to provide students with opportunities to learn electrochemistry from a macroscopic, sub-microscopic, and symbolic lens. Benjamin explained:

> It's a lot of chemistry. You know, it goes back to the beginning of the year, even knowing the difference between an ion and atom. So you’re going back to, you know, the beginning of the year. So it’s a lot of chemistry within something as what we think is a
simple operating cell. I think they get confused between what is actually an anode and a
knowing how to write reactions, how to assign oxidation numbers.

Thus, students had a difficult time learning concepts but the teachers did not feel that the topic
was difficult to teach. If teachers did not find the topic difficult to teach, perhaps they were
unaware of the learning challenges students faced or the found it easier not to teach a sub-
microscopic lesson. In either case, TSPCK was lacking.

**Real world applications.** During the interview each candidate was asked to discuss the real
life applications of electrochemistry used in their instruction (Table 23). Teachers were only able
to articulate two to three examples of electrochemistry that they shared with their students. The
most common examples provided by teachers were ones typically present on the state assessment,
notably the plating of metals. Barbara, Roman, and Don also talked about electrolysis of water.
Roman talked about the production of sodium metal and Benjamin spoke of the production of a
substance. Besides those, the example of a battery charging or discharging was frequently cited,
for example, in a cell phone. Sarah even mentioned her lack of real world connections. In the
following statement, she acknowledged that her students did not make the connection between
what they were learning and real life but never stated she was lacking in her ability to facilitate
this. Rather, she placed the blame on her students:

> They just kind of learn what it is – electrolysis – and we tell them what it is, and there’s
> no connection to the real world for them. I mean, we could say they’re batteries, but it’s
> how the voltage is produced and how we get those numbers. I think that it’s a disconnect.

The teachers had previously been asked to list the real-life applications they use in this unit
during the TSPCK exam. The examples provided during the interviews, which were done six
months after the TSPCK exam, matched the exam questions. The intent of doing so was that the
time between data collection would increase the data reliability by triangulating sources.
### Table 23  
*Real Life Applications of Electrochemistry*

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Real Life Applications of Electrochemistry</th>
</tr>
</thead>
</table>
| Margene | Plating of silverware and comparison to real silver  
          | Plating of copper onto a penny/coin  
          | Re-chargeable battery |
| Alby    | Automotive and bicycle chrome bumpers  
          | Rim dipping  
          | Electroplating a metal |
| Sarah   | Electroplating silverware  
          | Electroplating Jewelry |
| Benjamin| Electroplating  
          | Producing a substance  
          | Cell phones |
| Barbara | Electroplating jewelry  
          | Electroplating metals  
          | Electrolysis of water  
          | Battery |
| Joey    | Battery/ Rechargeable batteries  
          | Electroplating in general  
          | Electroplating jewelry |
| Roman   | Electroplating metals  
          | Production of pure sodium metal  
          | Production of Hydrogen and Oxygen gas |
| Don     | Car Batteries  
          | Hoffman Apparatus  
          | Chlorine gas to treat sewage plants |

#### 4.8 Participant Summaries

All teachers discussed the difficulty students experience when trying to learn electrochemistry. The following quote from Sarah is indicative of the need for TSPCK in professional development:

> It's really a tough topic. It's a tough unit. The kids have trouble understanding it, so trying to come up with ways to make this simpler, you know, it’s hard. We’ve broken it down very simply and it’s still something that they struggle with. So it’s almost like I could use some more strategies to make them understand this a little bit better.
The availability of content specific professional development was lacking for the experienced chemistry teachers in this study. While these teachers were experienced and participated in a professional learning community, this did not guarantee they possessed mastery of every topic within the discipline. None of the teachers in this study were provided with an opportunity to take a course in PCK, but only separate content courses in chemistry and pedagogical courses of broad applicable methods. The results of this study suggest the need for not only PCK coursework but TSPCK instruction. Due to the existing demands already present in the schedules of secondary high school teachers, seeking out relevant educational research is not an exercise in which teachers readily engage. To facilitate TSPCK development, new methods such as webinars, virtual learning, regional workshops, and alternate means need to be explored to connect research to practice.

**Composite scores.** Subjects received a TSPCK composite score based on their TSPCK exam and interview tasks. The following section describes how the TSPCK scores were calculated for each teacher. The five components of TSPCK were collapsed into three categories: 1) curricular saliency, which describes what curriculum the teacher planned to teach; 2) student learning challenges, which include the teachers’ understanding of what misconceptions and learning difficulties students have; and 3) teaching methodology, which included how the teacher taught the topic in the classroom. Each teacher was rated in each category as basic (1 point), proficient (2 points), or exemplary (3 points). Scores from each category were tallied for an overall composite score. Teachers who scored from 0-3 had basic TSPCK in electrochemistry, 4-6 were considered proficient, and 7-9 exemplary (Table 24).
<table>
<thead>
<tr>
<th>TSPCK</th>
<th>Curricular Saliency</th>
<th>Obstacles to Student Learning</th>
<th>Teaching Methodology</th>
</tr>
</thead>
</table>
| Basic  | - Provides one or no real life applications  
         - Instructional sequence shows lack of consideration of prior topics influence on student learning  
         - Depth of instruction is not appropriately distributed and test preparation outweighs student learning extensions | - Provides one to two learning difficulties to the topic  
         - Provides one to two misconceptions on the topic  
         - Incorporates at most, one form of representation (macroscopic, sub-microscopic or symbolic) into lessons | - Uses six or fewer teaching methods as the means to transfer knowledge  
*Teaching methodology includes: demonstrations, representations, analogies, POGIL, white boarding, lecture, cooperative learning, lab activities, explanations, etc.) |
| (1)    |                                                                                                                                                                                                                     |                                                                                                                                                                 |                                                                                                                                                      |
| Proficient | - Provides two or three practical, real world applications  
         - Makes an effort to incorporate prior topics to spiral curriculum  
         - Teacher touches slightly on content beyond that which will be covered on the final exam  
         - Instructional sequence evidences greater depth of consideration for how students learn. Some topics not taught to same degree. | - Provides three to four learning difficulties to the topic  
         - Provides three to four misconceptions on the topic  
         - Teaches the material with two forms of representation: macroscopic, sub-microscopic and symbolic representation into lessons | Uses nine or fewer teaching methods as the means to transfer knowledge                                                                                       |
| (2)    |                                                                                                                                                                                                                     |                                                                                                                                                                 |                                                                                                                                                      |
| Exemplary | - Able to provide four or more multiple real life applications and extensions of the curriculum  
         - Multiple connections and means to spiral curriculum  
         - Teacher is aware of final assessment, but also goes into detail on other topics not covered on the exam  
         - Instructional sequence evidences extensive consideration of presentation of topics and appropriate depth of instruction provided to all topics | - Provides more than 4 commonly held learning difficulties on the topic  
         - Provides more than 4 misconceptions on the topic  
         - Incorporates all levels: macroscopic, sub-microscopic and symbolic representation into lessons | - Incorporates ten or more methods/means of transferring knowledge                                                                                         |
| (3)    |                                                                                                                                                                                                                     |                                                                                                                                                                 |                                                                                                                                                      |
Margene: Exemplary TSPCK.

**Curricular saliency.** Margene scored a 2/3 for the domain of curricular saliency, as she was able to identify multiple real life applications, and provided a compelling rationale and sequence for topics that needed to be taught prior to electrochemistry. Additionally, she incorporated laboratories and simulations on cell potential, a topic not tested on the Regents examination, which demonstrates in-depth extension of the required curriculum.

Margene named seven topics that should be taught prior to electrochemistry instruction, including the mole concept, so that students could determine the number of electrons transferred when balancing half reactions. Additionally, she mentioned student understanding of atoms and ions so they could understand mass changes as well as conservation of mass in chemical reactions. A foundation of atomic structure is needed to understand the idea of electrostatic forces in electrochemical cells. Knowledge of periodicity is necessary to discuss metal and nonmetal reactivity. A foundation of reaction types is required to identify reactions such as redox. Finally, she explicitly contrasted aqueous solutions to salts and solid metals so students understand important aspects of solubility.

Margene’s sequential order began with oxidation numbers to serve as the foundation for the rest of the unit. This was followed by LEO/GER to identify the anode and cathode which led into defining the battery and how it works as an application to daily life. The next big idea focused on electroplating to show a real world example of how metal such as copper is plated at the cathode. Besides plating of silverware and comparison to real silver her instruction involved a laboratory where her students plated copper onto a penny/coin. Finally, she ended the unit with electrolysis instruction where she described how pure elements are obtained and discussed batteries and rechargeable batteries as authentic applications. Margene utilized three real life applications thus falls short in meeting the four or more real world applications to be exemplary. Additionally, Margene did not dedicate time to electrolytic cells or laboratories thus did not provide appropriate depth so scored a 2/3 for this section.

**Obstacles to student learning.** Margene scored a 3/3 in the domain of obstacles to student learning. She provided multiple examples of misconceptions and student learning challenges her students faced in learning electrochemistry. Additionally, she incorporated instructional strategies to address the three-fold representations of chemistry so her students could understand electrochemistry from a symbolic, sub-microscopic and macroscopic viewpoint. Her students completed a virtual laboratory where they were asked to compare the reactivities of various metals in solutions on a sub-microscopic scale. Additionally, her students completed a virtual lab on voltaic cells where they observed the change in voltage during the reaction and the students were able to see particulate activity. Students calculated voltage and created a symbolic representation of what they observed. Moreover, she showed her students a simulation to show the exchange of atoms and ions in the cell.

Margene identified a number of student misconceptions for redox and electrochemistry, such as the reversal of signs at the anode and cathode, and the erroneous ideas that multiple metals change phase, ions of the metal go through the salt bridge instead of within the solutions, and electrons go through the salt bridge. She also noted that students often confuse ions and atoms. Lastly, she described her students writing charges on atoms in reactions and their false notion that gaining electrons indicates the charge increased due to more substances being added.
Margene discussed several areas of obstacles to student learning. First, her students struggled with the anode losing mass and cathode gaining mass. They were confused by the process of atoms becoming ions and vice versa, and thought mass should be conserved so the anode mass itself should not decrease and cathode mass not increase to keep the mass constant. She found students often memorized definitions of electrical and chemical energy and did not fully comprehend what transpires in different types of cells. Although her students typically had a strong foundation of proton and electron charge, they still experienced difficulty when asked to write half reactions with balancing charge and mass of various atoms and ions.

**Teaching strategies.** For this domain, Margene scored a 3/3 for utilizing many means of knowledge transfer. Margene spent about 15 periods teaching oxidation, reduction and electrochemistry, and delivered content to her students via flipped videos. Her instruction involved whole class discussion, teacher explanation, completing practice problems on worksheets, reading about science, students using instructional technology, teacher demonstration, cooperative learning, students completing hands on laboratories, testing practice, representational drawings, simulation and animations, acronyms, and role play. She did not use any analogies in her instruction but did use the acronyms LEO and GER. For representations she drew Bohr diagrams, which are diagrams that show the atom along with the number of electrons in each shell to illustrate the difference between atoms and ions and electron transfer. She drew voltaic and electrolytic cells on the board with labels and performed a demonstration of a voltaic cell. This was followed by a video that explained the inside of a battery, which was related to the diagrams drawn on the board. She also demonstrated single replacement reactions to highlight the differences between spontaneous and nonspontaneous reactions and tasked her students with creating their own metal activity series. Students completed simulations to show the exchange of atoms and ions as well as voltage calculations. Additionally, she had her students complete a POGIL on voltaic cells. Process Oriented Guided Inquiry Learning (POGIL) is a research-based approach to teaching where students engage in chemistry activities collaboratively though active participation in a group role and uncover core concepts and engage in critical thinking (Moog & Spencer, 2008). Finally, she had her students pretend they were parts of a battery and move in paths around the room to simulate the cell. Margene’s overall composite score is 8/9 indicating exemplary TSPCK.

**Alby: Exemplary TSPCK.**

**Curricular saliency.** For this domain Alby scored a 2/3, as he was able to identify three real world examples of application of the concept and his instructional sequence showed great depth of consideration for how students learn. However, his instruction did not incorporate much material beyond the scope of the final exam and was thus lacking in extension, which he stated was due to the ability of the population he taught. Alby’s description of the topics that needed to be taught prior to instruction of electrochemistry began with atomic structure so students could understand the difference between atoms and ions. He also included nomenclature and formula writing, bonding for compound formation, the mole and stoichiometry for understanding reaction types, and balancing moles of atoms and ions. Finally, he stated matter and solutions should be taught prior to electrochemistry to provide students with knowledge of how atoms and ions distribute in aqueous solutions.

Alby’s instructional sequence began with assigning oxidation numbers so that students could track the movement of electrons. This was followed by how to write and balance half redox
reactions so that students could observe the movement of electrons as well as conservation of charge. Lastly, he taught voltaic cells so students could understand the movement of electrons to power electrical energy. Alby omitted the topic of electrolytic cells, however, he did include the topic on his concept map. The concept map employed by Alby was less a true concept map and more of a flow chart (Figure 18). In a follow up interview for substantive validity, Alby indicated he was not sure how to create a concept map and instead illustrated his sequence of topics taught for the unit.

![Concept Map](image)

*Figure 18. Teacher TSPCK response 6.*

Alby incorporated the following real life examples in his instruction: automotive and bicycle chrome bumpers, rim dipping, and electroplating a metal. The first two examples listed are examples not suggested on the Regents exam and examples to which this particular population of students could relate. Like Margene, Alby was lacking in his macroscopic instruction of electrolytic cells via demonstration or activity.

**Obstacles to student learning.** Alby received a score of 2/3, proficient in this category. For identifying student difficulty he incorrectly stated that only mass and not charge must be balanced, when, in fact, both mass and charge need to be balanced. Alby identified one area of learning difficulty but multiple areas of student misconception. He also incorporated multiple representations of chemistry to students via simulations.

Alby identified balancing redox reactions as an area of learning difficulty for students, as they often “balance mass instead of charge when asked to balance.” Alby identified the misconception that atoms and ions are synonymous. He identified a misconception in regard to
electrolytic cells that the metal being plated is oxidized or reduced. For voltaic cells, he identified the following student misconceptions: electrons stop at the cathode, electrons flow through the salt bridge, ions flow through the wire, electrons always flow from left to right and finally that electrons being lost what is caused the loss of mass of the anode and vice versa.

**Teaching strategies.** For this domain, Alby received a 3/3, exemplary TSPCK, as he utilized ten or more methods of instruction. Alby’s teaching methods included: flipped videos, whole class explanation and discussion, students working independently on practice problems and standardized test problems, simulation, students completing hands on laboratories and activities, drawing diagrams, cooperative learning activities, teacher conducted demonstrations, students using instructional technology, and reading about science. Ably did not use analogies in his instruction of electrochemistry.

Alby stated he built a working voltaic and electrochemical cell and had students use that as a guide when working on problems. He was unclear how the electrochemical cell is different than the voltaic cell and it is possible he was confusing the two, however, in a follow up interview he indicated he did not demonstrate electrolytic cell just a voltaic cell. He had his students come up to the cells in the front of the room and they described what was occurring with a description of electron flow. He also had his students illustrate diagrams to visualize what was occurring. Finally, his students manipulated virtual cells via simulations, which demonstrated understanding of half reactions and half-cells at the atomic level. Alby has an overall composite score of 7/9 thus demonstrating overall exemplary TSPCK.

**Sarah: Proficient TSPCK.**

**Curricular saliency.** For this domain Sarah showed basic TSPCK, scoring 1/3, as she was limited in the amount of real life applications provided to her students, lack of consideration of prior topics, and taught a curriculum strictly based upon the final assessment. Sarah began her unit on electrochemistry with assigning oxidation numbers so students could determine which species gained electrons and which species lost electrons. This was followed by instruction on the definitions of oxidation as loss of electrons and reduction as gain electrons. By doing so, students were able to map out the flow of electrons and determine what was oxidized and what was reduced. This was followed by instruction on how to write half reactions to determine the number of electrons transferred. Next, students were taught about galvanic cells using all the previous knowledge taught to label a diagram and understand how a simple battery works. Lastly, students learned about electrolytic cells with diagrams to explain how electrical energy could be used to initiate a nonspontaneous redox reaction.

Sarah described the significance of prior knowledge related to electrochemistry including the difference between atoms and ions, as well as symbols so students could write reactions and assign oxidation numbers. Since voltaic cells require solutions for the metals to be oxidized or reduced, she stated students should understand solution chemistry and writing and balancing reactions. Sarah named a few topics that should be taught prior but without significant rationale. For example, she stated that students should know what solutions are in general since the metals (referring to the anode and cathode) are placed in solutions. The explanation failed to describe the benefits of understanding why the metals are placed in solutions.

At multiple times throughout her interview Sarah mentioned she felt constrained by the Regents exam. She did not extend her curriculum beyond the scope of the Regents curriculum.
and did not provide any higher level or extensions for electrochemistry. For real life applications she taught electroplating jewelry and silverware since those are commonly assessed.

**Obstacles to student learning.** For this domain Sarah received the score of 1/3, as she was not able to identify many student learning difficulties or misconceptions related to the topic. She did incorporate one computer simulation activity to show the sub-microscopic nature of chemistry. Additionally, she taught her students half-reactions using equations to represent reactions symbolically what they had observed macroscopically through labs and demonstration.

Regarding student misconceptions, Sarah identified that students sometimes did not understand that if one species loses electrons the other must gain the same number of electrons. For voltaic cells she identified that students sometimes believe that electrons flow through the salt bridge and that the anode and cathode are the entire half-cell – not the metal itself. Sarah was able to describe student misconceptions for redox and voltaic cells but was not able to do so for electrolytic cells. She believed that oxidation was difficult to learn because of confusion regarding movement of electrons and corresponding changes in oxidation number.

**Teaching methodologies.** Sarah scored proficient in this category 3/3. She devoted 16 periods of instruction to the teaching of redox and electrochemistry. Her main means of content delivery were traditional lecture and flipped videos. Her instruction included teacher explanation, whole class discussion, students working on practice problems or worksheets, students using instructional technology, simulation, cooperative learning, laboratory activities, diagram representations, and teacher demonstration. Sarah stated her students completed a lab with redox reactions where they reacted a zinc core of a penny with acid. Her instruction did not include the use of textbook, students reading about science, or analogies. Her overall composite score is a 5/9 thus her TSPCK is proficient.

**Benjamin: Proficient TSPCK.**

**Curricular saliency.** Although Benjamin possessed sound knowledge of what topics should be taught prior to electrochemistry, he only provided two real life applications and provided a curriculum limited in its scope with heavy emphasis on the final exam, scoring a 1/3 for this domain. When discussing prior knowledge, he included atomic structure because he believed students need to understand how and why ions form. He stated that students must understand the difference between elements and compounds, how a mixture differs from a compound, and how to read the periodic table. Students should be able to interpret names or formulas and how to read an equation in terms of what is happening in the reaction. They should recognize what is happening with electrons during bond formation as well as different types of bonds, and should understand how to perform calculations that may be part of a redox reaction in terms of mole ratios. They should know whether a substance is soluble, what happens when it is in solution, how ions dissociate, and what types of ions are present in a solution.

Benjamin demonstrated detailed reasoning behind the order in which he presented concepts. He started the electrochemistry unit by teaching oxidation numbers, followed by writing half reactions, then electrochemical cells. Benjamin had difficulty creating a concept map to show the interconnectedness of the ideas and had multiple cross outs. After completing this portion of the interview, he explained he had not received formal training in concept maps and was unsure how to go about this. Even after he was provided an example for another topic he remained unsure.
In terms of real world applications, Benjamin discussed electroplating metals and jewelry, batteries and electrolysis of water. At multiple points during the interview Benjamin mentioned the importance of the final exam on the curriculum taught. He specifically mentioned he finished the curriculum six weeks early to allow for preparation for the Regents exam. He mentioned that this was the last unit of instruction so he limited the number of activities and laboratories due to the importance he placed on allocating time for final exam review, despite the fact that he stated he spent 25 hours on the unit.

**Obstacles to student learning.** Benjamin exhibited proficient (2/3) TSPCK in this domain. He identified students having alternate ideas about what is oxidized and reduced, how to correctly write half reactions, mass changes at the electrodes, salt bridge function, half reactions of molten salts, and the purpose of a battery in an electrolytic cell. Benjamin mentioned two topics as difficult for students to learn – 1) correctly balancing half reactions when describing molten salts, and 2) substituting nonmetal atoms with ions due lack of familiarity with nonmetals when compared to the activity series for metals.

Benjamin was able to identify multiple misconceptions for students, specifically that mass and charge do not need to be equal, that the anode gets smaller because it loses electrons while the cathode gets bigger because it gains electrons and that electrons travel through the salt bridge. As far as the threefold nature of chemistry, Benjamin drew the diagrams on the board to explain the sub-microscopic nature of voltaic and electrolytic cells.

**Teaching strategies.** For this section Benjamin scored a 1/3, demonstrating basic TSPCK. He used flipped learning as a means of content delivery. Prior to the study Benjamin used mainly lecture. An additional method included playing an online game called Kahoot where students answered questions via a remote clicker. He used an animation to show atoms becoming ions and ions becoming atoms at the anode and cathode to illustrate the sub-microscopic representation. He utilized diagrams of voltaic and electrolytic cells and explained electrolysis of water and molten salts as well as the application of plating. Students completed practice problems and practice for standardized tests. Benjamin’s overall composite score is a 5/9 thus he exhibited proficient TSPCK.

**Barbara: Exemplary TSPCK.**

**Curricular saliency.** Barbara taught her Regents level students well beyond the scope of the curriculum. Barbara’s TSPCK in this domain receives a 3/3 since she provided multiple real life applications and extensions of the curriculum, logical learning progressions, and at no point mentioned the Regents exam as a limitation of content depth.

When asked to describe the definitions of oxidation and reduction provided to students, Barbara was the only teacher to incorporate all definitions, showing the dynamic nature of scientific theories. She was able to provide a logical order and rationale for her curriculum sequence. For example, she explained that students must have an understanding of atomic structure to understand the nature of atoms and ions, periodic table to understand the activity series, and stoichiometry for students to understand mole ratios and quantify electrolysis.

Barbara mentioned the importance of spiraling the curriculum to reinforce prior chemistry concepts. When asked to describe the sequence of topics taught, she followed a logical progression with a clear rationale. She started with definitions of oxidation and reduction, followed by writing half reactions to set up the process of redox reactions, followed by balancing
half reactions to expose students to the idea that oxidation and reduction occur simultaneously. She then discussed spontaneity to link the activity series to redox reactions and introduced galvanic and electrolytic cells. Barbara’s concept map showed interconnections within the unit. She incorporated electroplating jewelry and metals in general, along with discussion of batteries and electrolysis of water.

**Obstacles to student learning.** For this domain Barbara received a 2/3 because she was able to provide two learning difficulties related to the topic, three misconceptions on the topic, and had an instructional sequence that indicated greater depth of consideration for how students learn. However, she was missing sub-microscopic representations in lessons and stated that she did not approach her teaching from this perspective.

Barbara was able to identify the following three common student misconceptions: 1) oxidation and reduction do not need to occur simultaneously, 2) electron flow constitutes current in electrolytes, and 3) students frequently change the charge of the signs of the anode and cathode. With regards to student learning difficulties she identified that students find the definitions for this topic confusing and commonly misunderstand the processes. Of particular difficulty is the concept of cell potentials, since her students typically had not yet taken physics.

One potential area for improvement would be her explanation of chemistry from multiple perspectives. Barbara mentioned she did not use simulations or animations, as she had not noticed her students struggling with sub-microscopic understandings. While she described what ions and atoms were she did not require students to draw them or explain how they believed they would appear on a sub-microscopic level.

**Teaching strategies.** Barbara’s teaching methods included traditional lecture, teacher demonstrations, laboratory activities, drawing diagrams, analogy, acronym, textbook reading, and lecture. For this domain she scored a 3/3. Her main mode of instruction was lecture. To introduce electrochemistry she showed the students a rusty nail and initiated a discussion of oxidation. She also presented the students with an electrolytic cell to demonstrate the electrolysis of copper (II) chloride solution and allowed the reaction to follow its course for the entire day so students could diagram what they observed; they also explained why they believed the chlorine gas was being produced and where and how the copper was depositing. As for laboratory exercises, she adapted traditional copper plating to a silver mirror activity. Additionally, she incorporated a “mini-voltaic cell lab” where students determined the difference in potential between various metals, or a lab where students investigated oxidation states. Barbara used the analogy of a waterfall moving in one direction to help students understand the idea of potential difference. She drew a picture of an OIL RIG as an acronym to remind students that oxidation is losing electrons and reduction is gaining electrons. She also drew diagrams on the board with her students to explain what voltaic and electrolytic cells look like. Barbara was one of the only teachers to require students to read the textbook and complete a study guide based on the reading. Barbara’s overall composite score was 8/9, indicating that she exhibited exemplary TSPCK.

**Joey: Proficient TSPCK.**

**Curricular saliency.** For this domain Joey scored a 1/3 due to several limitations. He provided a vague overview of foundational topics prior to electrochemistry, stating basically everything except the topics of organic and nuclear. He mentioned that students should
understand solutions and electrolytes for discussion of the salt bridge, and they should be able to identify ions and atoms to understand voltaic and electrolytic cells.

His instructional sequence began with a discussion of oxidation numbers, oxidation and reduction since they constitute the foundation of the rest of the unit. This was followed by balancing redox reactions, which combined the basic processes of oxidation and reduction to form a reaction and demonstrated conservation of charge. Next, Joey taught voltaic cells and this was followed by electrolytic cells to illustrate authentic applications. Besides batteries, Joey discussed the processes of recharging batteries and electroplating metal and jewelry. Joey did not mention being limited by the Regents exam but did not offer any further extensions or applications of the curriculum.

**Obstacles to student learning.** Joey scored a 1/3, basic TSPCK, as he demonstrated insufficient knowledge of student learning difficulties in electrochemistry. He only taught honors and AP level students which may have contributed to his lack of awareness. When asked to identify student misconceptions, Joey only noted one – that students have difficulty identifying the anode and cathode versus what substance is actually being oxidized and reduced. For student learning difficulties Joey only noted that electroplating is difficult, specifically half reactions at the anode and cathode, because students had trouble when the same substance was both oxidized and reduced. Moreover, Joey did not incorporate any simulation, animation, or drawing of the sub-microscopic nature of what occurred at the anode of cathode in a voltaic or electrolytic cell.

**Teaching strategies.** Joey scored a 2/3 or proficient TSPCK for teaching strategies. The main means by which content was delivered in his class was lecture. He spent 20 periods teaching the unit via whole class discussion, cooperative learning, labs, demonstrations, and students reading about science. He had his students complete a reactivity of metals lab, practice problems and they watched a video on electrochemistry. Joey’s overall composite is a 4/9 showing proficient TSPCK.

**Roman: Exemplary TSPCK.**

**Curricula saliency.** When asked what topics should be taught prior to electrochemistry, Roman first suggested identification and assignment of oxidation numbers. Additionally, he suggested conservation of mass and energy, since electrochemistry exemplifies these larger concepts. His curricular sequence started with overarching concepts, the first of which was chemical energy being converted to electrical energy to show conservation. This was followed by the idea that chemical reactions could be driven by exchanges of electrons as the foundation for redox. Finally, he introduced the idea of electrical energy being converted to chemical energy to show that energy exchange works in both directions.

When asked to describe real life applications, Roman described three means by which he connected electrochemistry authentic contexts: electroplating metals, production of pure sodium metal, and production of hydrogen and oxygen gas as well as wet cells. He taught his students about cell potential, a topic not required for the curriculum, which showed extension of content. While Roman had his students draw models of electrolytic cells, he did not macroscopically show his students an electrolytic cell demonstration or have his students complete a laboratory related to electrolytic cells, thus did not provide adequate depth of student activities. For this category he scored a 2/3.
**Obstacles to student learning.** Roman scored a 2/3 for this domain as he provided sufficient misconceptions but was lacking when it came to providing multiple reasons why electrochemistry is difficult for students to learn. He probed his students at the beginning of the unit to assess what students already knew. He was one of the only teachers who tried to determine prior knowledge. He identified the following student misconceptions: reactions can be balanced in terms of mass without balancing the charge, reduction is the loss of electrons, that the loss of anode mass is due to electrons not ions, that electron flow proceeds from the less active metal to the more active metal, and reduction happened at the anode and oxidation at the cathode in electrolytic cells since the charge of the electrodes is reversed.

Roman found it difficult for students to understand voltaic cell structure and function, as it was challenging for them to visualize the chemistry and the functions of each part. Roman taught AP Biology and had a completely different conceptualization of big ideas related to structure and function, and he taught the major theme of energy more in line with a biology curriculum organization. For the sub-microscopic level of representation, Roman showed his students computer animations and videos of the cells. He also had his students use white boards to model cell function in terms of atoms and ions.

**Teaching strategies.** Roman scored a 3/3 for this domain. He dedicated about 15 periods of instruction to teaching redox and electrochemistry. The content was delivered to the students via traditional lecture, videos, and other means other than textbook readings. During this unit students worked in cooperative groups, engaged in hands on and laboratory experiences, and used instructional technology. He explained science concepts, facilitated whole class discussion, and showed his students a demonstration. For demonstrations he used a POE model to show students steel wool in copper (II) sulfate, a Hoffman voltmeter, and an example of a wet cell. Students used white boards to create models for what was occurring sub-microscopically in the voltaic and electrolytic cells by drawing what would happen if aluminum were placed in copper (II) sulfate. Roman used the analogy of bullies as less active metals and his instruction of electrochemistry. Additionally, Roman used representations such as cell diagrams including voltaic and electrolytic, fused salts, water, and plating, as well as an activity series and reduction potential chart. Roman’s overall TSPCK score was 7/9, exemplary.

**Don: Exemplary TSPCK.**

**Curricular saliency.** Don scored a 3/3 for providing a detailed list of topics that need to be taught prior to electrochemistry along with a rationale. He started with atomic structure because his students needed a refresher about ions, how they are formed, and the charges associated with each. He included bonding since the transfer of electrons is discussed. To understand oxidation states, students need to know how to name and write chemical formulas for compounds. Chemical equations and reactions served as the main building block for teaching oxidation-reduction. Don spiraled back to these reactions to discuss what makes something a redox reaction. He included solutions for students to explain the movement of ions in solution for galvanic cells. Finally, the concept of electrolytes was taught as well as acids and bases so students could understand how solutions with ionic compounds carry an electric current.

Don utilized real world examples such as a cell phone running and charging to describe the difference between spontaneous and non-spontaneous reactions. He discussed the Hoffman apparatus and the use of chlorine gas to treat sewage plants. He mentioned he taught cell potentials to his honors students only, not his Regents classes since it was not covered on the
Regents exam. Additionally, he mentioned he did not teach cell potential every year so he needed to review the material prior to instruction. However, he did teach oxidizing and reducing agents, which are not assessed on the Regents exam.

Don’s instructional sequence and rationale indicate much thought went into the planning of the unit. First he discussed the rules governing oxidation states, which was introduced during bonding and then reviewed at the start of electrochemistry. This was necessary to determine whether the reaction was a redox reaction. This was followed by a review of the oxidation states to be able to determine whether there was a change and identify the substance oxidized and reduced. This was followed by half reactions in which he used a number line to show oxidation and reduction. Reducing agents and oxidizing agents were then introduced and this was followed by discussion of activity series. Voltaic cells were then taught to illustrate the activity series. Last, the Hoffman apparatus was used to show electrolytic cells as well as discussion of the key differences between voltaic and electrolytic cells. Don utilized multiple methods of displaying the macroscopic level of representations, but lacked in his employment of sub-microscopic.

**Obstacles to student learning.** When asked to describe student misconceptions, Don mentioned 1) confusing the substance oxidized and the oxidizing agent, 2) the idea that free elements are not charge, and 3) loss of electron lowers the charge of the oxidation state. For voltaic cells, Don described two misconceptions: 1) electrons flow through the salt bridge, and 2) electricity is made of electrons so it must be electrons that travel through. Additionally, he stated his students think that the negative electrode is where electrons go. For electrolytic cells during electroplating, students sometimes incorrectly think that the metal source for plating will decrease in mass. Additionally, there is often confusion as to the direction of ion movement toward electrodes as the charges of the anode and cathode are reversed when compared to a galvanic cell. When describing what his students find difficult to learn, he described the halogen activity series when discussing non-metals despite understanding the idea for metals. Don did not have an activity where students drew or explained electrochemistry from a sub-microscopic viewpoint, thus for this section scored a 2/3.

**Teaching strategies.** For this section Don scored a 3/3. He spent about 15 periods teaching redox and electrochemistry. His main method of delivering the content was traditional lecture, textbook readings, and demonstration. His instructional unit included whole class discussion and time where students completed textbook work, read about science, completed hands on laboratory work, worked in cooperative groups, learned acronyms, and practiced for standardized tests. Don used the analogy of a secret agent giving or taking secret documents (the electrons) for agents of redox. Don used the acronyms LEO, GER, RED CAT, and AN OX. For representations, Don placed a copper/zinc electrochemical cell on his desk throughout the unit demonstrating the changes in the metals over time. He also had them build their own batteries from lemons or other fruit, and had various simulations which showed how batteries work. He also used all the traditional diagrams from the Regents exams, which showed electrochemical and electrolytic cells, including hydrolysis and electrolysis. Finally, Don demonstrated a Hoffman apparatus as well as pre- and post-1982 pennies. Don’s overall composite is a 8/9 thus exemplary TSPCK.

A summary of teacher TSPCK is presented in Table 25. The overall TSPCK composites of the experienced chemistry teachers may be found in Table 26.
<table>
<thead>
<tr>
<th>Subject</th>
<th>Curricular Saliency</th>
<th>Obstacles to Student Learning</th>
<th>Teaching Strategies</th>
</tr>
</thead>
</table>
| Margene | • Instructional sequence evidences extensive consideration of 7 topics with rationale that should be taught prior to electrochemistry  
• Real-life application included: plating of silverware and comparison to real silver, plating of copper onto a penny/coin, rechargeable battery  
• Extends curriculum with higher level topics such as cell potential  
• Lacked in electrolytic cell demonstration or laboratory activities | • Students’ misconceptions/difficulty include: reversal of signs at the anode and cathode, multiple metals change phase, ions of the metal go through the salt bridge instead of within the solutions, electrons go though the salt bridge, difference between atoms and ions, and gaining electrons indicates the charge increased due to more substances being added.  
• Incorporated all levels: macroscopic via voltaic cell lab and diagrams, symbolic through flipped videos and explanation via equations and submicroscopic and through virtual lab simulations and animations | Flipped videos, whole class discussion, teacher explanation, student completion of practice problems on worksheets, reading about science, students using instructional technology, teacher demonstration, cooperative learning, hands on laboratories, representational drawings, simulation and animations, acronyms, role play and practicing for standardized tests. |
| Alby | • Instructional sequence evidences extensive consideration of 5 topics with rationale that should be taught prior to electrochemistry  
• Real-life application included: Automotive and bicycle chrome bumpers, Rim dipping, Electroplating a metal  
• Curriculum limited by the final exam  
• Lacked in electrolytic cell demonstration or laboratory activities | • Students’ misconceptions/difficulty include: atoms and ions are the same, products are oxidized and reduced, electrons stop at the cathode, electrons flow through the wire, loss of electron causes the anode to lose mass, electrons always flow from the left to the right, the metal being plated is oxidized or reduced, balancing mass and not charge in a redox reaction.  
• Incorporated all levels: macroscopic via voltaic cell lab and diagrams, symbolic through flipped videos and explanation via equations and submicroscopic and through virtual lab simulations and animations | Flipped videos, whole class discussion, teacher explanation, student completion of practice problems on worksheets, simulation, hands on laboratories and activities, drawing diagrams, cooperative learning activities, teacher conducted demonstrations, instructional technology, reading about science, and practicing for standardized tests. |
| Sarah | • Instructional sequence evidences extensive consideration of 4 topics with rationale that should be taught prior to electrochemistry  
• Real-life application included: Electroplating, silverware and jewelry  
• Curriculum limited by the final exam | • Students’ misconceptions/difficulty include: electrons travel through the salt bridge, anode is the ½ cell not he metal, number of electrons lost equals, if one species loses electrons the other species gains the same amount, loss of electrons indicates a loss | Traditional lecture, flipped videos, teacher explanation, whole class discussion, students working on practice problems or worksheets, students using instructional technology, simulation, cooperative simulation, laboratory activities, diagram |
<p>| Benjamin 1+ 2 +2= 5 | Instructional sequence evidences extensive consideration of 8 topics with rationale that should be taught prior to electrochemistry • Real-life application included: Electroplating producing a substance, cell phones • Curriculum limited by the final exam • Lacked in electrolytic cell demonstration or laboratory activities | Students’ difficulties include: Cathode and anode are the same as the substance oxidized or reduced, substance oxidized or reduced when the same substance is oxidized or reduced • Incorporated all levels: macroscopic via voltaic cell lab and diagrams, symbolic through flipped videos and equations on the board and sub-microscopic by showing her students a simulation. | Traditional lecture, teacher demonstration, laboratory activities, drawing diagrams, analogy, acronym, use of technology textbook reading, teacher explanation, and practicing for standardized tests. |
| Barbara 3 + 2 + 3= 8 | Instructional sequence evidences extensive consideration of 4 topics with rationale that should be taught prior to electrochemistry • Real-life application included: Electroplating jewelry, electroplating metals, electrolysis of water and batteries • Extends curriculum with higher level topics such as cell potential with electrolysis demonstrations | Students’ misconceptions/difficulty include: oxidation and reduction do not occur simultaneously, electrons lost are the electrons gained, flow of electrons is not caused by potential difference, incorrect charges on the electrodes on electrolytic cells, oxidized substance is the oxidizing agent, acronym confusion, potential difference confusion • Limited in microscopic representations | Teacher explanation, whole class discussion, teacher demonstration, laboratory activities, drawing diagrams, analogy, acronym, textbook reading, reading about science, and practicing for the standardized tests. |
| Joey 1+ 1 + 2= 4 | Instructional sequence evidences extensive consideration of 2 topics with rationale that should be taught prior to electrochemistry • Real-life application included: Battery/ Rechargeable batteries, electroplating in general, electroplating jewelry and metals • Lacked in electrolytic cell demonstration or laboratory activities • No extension or further curricular applications | Students’ difficulties include: Difference between anode and cathode verse substance oxidized, determine the half-reaction when the same substance is oxidized and reduced. • Limited in sub-microscopic representations | Teacher explanation, whole class discussion, teacher demonstration, hands on laboratories, practice worksheets, cooperative learning, use of instructional technology, students reading about science, and practicing for standardized tests. |
| Roman 2 + 2 + 3= 7 | Instructional sequence evidences consideration of 2 topics with rationale that should | Students’ misconceptions/difficulty include: reduction is loss of | Teacher explanation, whole class discussion, teacher demonstration, hands on |</p>
<table>
<thead>
<tr>
<th>Instructional sequence evidences extensive consideration of 5 topics with rationale that should be taught prior to electrochemistry</th>
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<tr>
<td>Students misconceptions/difficulty include: substance oxidized is oxidizing agent and vice versa for reduction, oxidation number of a free element is the charge of the metal when it forms an ion, loss of electrons lowers the oxidation number, gain of electrons makes the oxidation number increase, electrons flow though the salt bridge, electrons travel to the negative electrode always, when plating an object the mass of the electrode decreases, positive ions move towards the anode</td>
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<td>Limited in sub-microscopic representations</td>
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<th>Real-life application included: electroplating metals, production of pure sodium metal, production of Hydrogen and Oxygen gas</th>
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<tr>
<td>Incorporation all levels: macroscopic via voltaic cell lab and diagrams, symbolic through teacher explanation and explanation via equations and sub-microscopic and through modeling with white boards and computer animations and videos of the cells as well as computer animation and simulations</td>
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<th>Curriculum limited by the final exam</th>
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<tbody>
<tr>
<td>Teacher explanation, whole class discussion, teacher demonstration, hands on laboratories, practice worksheets and practicing, cooperative learning, students completing textbook work, acronyms, analogies, students reading about science, and practicing for standardized tests.</td>
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<td>Teacher explanation, whole class discussion, teacher demonstration, hands on laboratories, practice worksheets and practicing, cooperative learning, students completing textbook work, acronyms, analogies, students reading about science, and practicing for standardized tests.</td>
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Table 26
*TSPCK Composite Scores*

<table>
<thead>
<tr>
<th>Subject</th>
<th>Curricular Saliency</th>
<th>Student Learning Difficulty</th>
<th>Teaching Methodology</th>
<th>Composite</th>
<th>Critical Thinking Learning Gain</th>
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</thead>
<tbody>
<tr>
<td>Margene</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>8 - exemplary</td>
<td>.39</td>
</tr>
<tr>
<td>Alby</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>7 - exemplary</td>
<td>.37</td>
</tr>
<tr>
<td>Sarah</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>5 - proficient</td>
<td>.29</td>
</tr>
<tr>
<td>Benjamin</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5 - proficient</td>
<td>.61</td>
</tr>
<tr>
<td>Barbara</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>8 - exemplary</td>
<td>.64</td>
</tr>
<tr>
<td>Joey</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4 - proficient</td>
<td>.68</td>
</tr>
<tr>
<td>Roman</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>7 - exemplary</td>
<td>.51</td>
</tr>
<tr>
<td>Don</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>8 - exemplary</td>
<td>.31</td>
</tr>
</tbody>
</table>

4.9 Participant Composites and Student Assessment Data

As mentioned in Section 4.4, the data were analyzed using a Wilcoxon signed-ranks test, indicating that critical thinking post-test scores were significantly higher than critical thinking pre-test scores, thus student learning did occur. The students of several teachers had normalized gains that were statistically similar, as indicated by means and standard errors (Figure 19). There were large standard deviations for the normalized gains of students from schools with high populations of low SES (Table 10). The lower the SES the wider the range of results obtained compared to higher SES students whose standard deviation were more narrow. This suggests that the students in higher SES showed little variation on the exams, performing quite similarly to one another whereas the lower SES students had a relatively wide range of scores. Thus within those schools with greater standard deviations there exists students who perform at a very low level as well as students who perform at a high level whereas in higher SES schools students’ scores were more clustered in their results, not only performing higher but clustered closer to the mean.
Margene and Alby had similar gains and both work in the same school district. Sarah and Benjamin also work in the same district and have similar learning gains. Roman works in a low SES district but had high TSPCK. Joey’s students had the highest learning gain and also works in a school district with the highest SES of the teachers in the sample. The next highest SES district of the sample was that of Barbara’s students who showed the second highest learning gains. The teachers in low SES districts tended to have higher TSPCK than indicated by student learning gains. Teaches in high SES districts such as Barbara, Don and Joey had higher student learning gains but not necessarily higher TSPCK composites. Thus while TSPCK affected student learning, SES was more strongly correlated. TSPCK is not only topic specific, but audience specific, as well; thus, when examining teachers’ abilities to transfer knowledge, a multi-dimensional process is presumed.

In summary, it is difficult to measure teacher competency on student outcomes when students vary so much year to year. A comparison of TSPCK composite and student learning gains indicated that there is not a direct correlation (Figure 20). Don, Barbara and Margene all demonstrated high TSPCK, yet their students did not perform similarly. An implication is that regardless of the TSPCK of the teacher, students in high SES districts will outperform those in low SES districts. This may be attributed to a variety of factors such as a small sample size per teacher or that students vary from year to year. Additionally, the data were self reported and teacher observations were not conducted. Not only is the emphasis on testing students limiting the teacher TSPCK development, the test itself may not be equitable.
Figure 20. TPSCK impact on student learning gains for critical thinking questions.
Chapter 5

Summary, Implications & Recommendations

5.1 Summary

This study sought to examine the TSPCK of eight experienced chemistry teachers in electrochemistry. Electrochemistry is typically understood to be a challenging topic for students (Sanger & Greenbowe, 1997). They often hold misconceptions about the topic, which confound their ability to grasp the content (Barke et al., 2009). Since students entered the course with very little content knowledge, it was appropriate to investigate how the teachers transformed their own understanding of the content into meaningful information and experiences for students.

This research continues the work of previous researchers such as Van Driel et al. (1999), who led the field in the study of a topic specific approach to examining teacher PCK. The theoretical framework for this study is built upon components of TSPCK that were identified by the research of Mavhunga (2012) to include the learner’s prior knowledge, what makes the topic easy or difficult to teach, curricular saliency, representations including analogies and conceptual teaching strategies. The work of van Driel et al. (1999) explored topic specific PCK, but did not examine PCK through the lens of a TSPCK exam and interview tasks. Mavhunga and Rollnick (2013) developed and validated a TSPCK exam as means of assessing teacher TSPCK. This study built upon their work by defining the electrochemistry TSPCK construct via a TSPCK exam in conjunction with tasks designed to capture a snapshot of the teachers’ PCK as opposed to just a content knowledge exam and TSPCK exam. Furthermore, this study sought to determine the relationship between TSPCK and student learning outcomes.

To examine each component of TSPCK, data were collected from a variety of sources, the first of which was a pre- and post-assessment of the teachers’ students regarding their knowledge of redox and electrochemistry. By gathering student data, TSPCK outcomes could be compared to determine if there were a correlation between student outcomes and teacher TSPCK. In an effort to identify the subjects’ TSPCK, instruments were modified to provide an accurate assessment of each participant’s TSPCK. The Horizon instrument was adapted to elicit demographic information from the participants as well as obtain information regarding pre-service preparation and in-service professional development as it related specifically to electrochemistry TSPCK. The TSPCK exam developed by Rollnick and Mavhunga (2014) was modified and piloted multiple times to properly align with the NYS curriculum and to ensure that the instrument elicited the information necessary to answer the research questions. After multiple revisions with science education and chemistry faculty, the exam was piloted and additional revisions were made prior to administration. The final component of data collection involved teacher interviews, during which subjects responded to prompts and tasks to demonstrate their TSPCK of electrochemistry. The tasks were developed, piloted, and modified with science education faculty prior to subject interviews.

This case study sought to identify shared patterns and trends observed in eight experienced chemistry teachers who participated in the same professional learning community. There was
evidence of teachers lacking in certain areas of TSPCK suggesting the need for programmatic improvements in pre-service training and in-service professional development. The following section summarizes the major trends that were observed.

**Student performance.** The subjects’ students showed very little knowledge of electrochemistry as evidenced by a pre-test on the topic. Students showed significant learning gains from the pre- to post-assessment, in both overall knowledge and critical thinking. While the learning gains were not directly tied to teacher TSPCK, they were confounded by other factors. The learning gains showed a moderate correlation with SES of the school districts, where high SES students in general out preformed low SES students, even when the teacher of those students had high TSPCK. Thus, regardless of the ability of the teacher to transform content knowledge, the students in high SES districts were generally successful on Regents type questions.

**Curricular saliency.** Overall, experienced teachers provided a rationale for the order they believed curricular topics should be presented and to what extent they should be expanded. For instance, all teachers recognized that students needed to have a foundation of oxidation numbers prior to explaining half-reactions for oxidation and reduction. Teachers had a variety of means by which they spiraled previously learned topics into the curriculum, such as the difference between atoms and ions, types of reactions, formula and equations.

All teachers were constrained by the amount of content that needed to be taught. The teachers felt as though they were “marching through” content without providing the students with the proper experiences necessary to gain conceptual understanding. Many teachers discussed the pressure to finish the curriculum in order to have additional time to review for the state mandated final assessment. The emphasis on lesson design seemed overly focused on “teaching to the test” as teacher performance was evaluated based on Regents exam scores.

The most common real world examples provided by teachers were ones typically present on the state assessment, notably the plating of metals. While teachers stated the motivation for teaching the unit was that it is relevant and applicable to students’ daily lives, the few examples chosen by teachers to connect the content to life outside the classroom were trivial. While most students had or are at least familiar with cell phones, only one teacher made the connection between electrochemistry and charging cell phone batteries. The narrowness in scope of the final exam limited the extension of curriculum to real life applications that could further the students’ interest in electrochemistry.

The results of the study revealed that most teachers spent very little time teaching beyond the boundaries of the curriculum. Thus, after completing the NYS chemistry course students progressed in their academic career without exposure to many of the authentic applications of chemistry they may encounter as professionals, such as fracking, industrial processes, or salt formation. These concepts hold tremendous relevance and lack of exposure to such concepts may limit their desire to study post-secondary chemistry.

**Obstacles to student learning.** The three-fold nature of chemistry (macroscopic, sub-microscopic, and symbolic) is one of the challenges students face when learning chemistry. It was evident that some teachers emphasized one domain over others and perhaps due to time constraints did not have the opportunity to focus on making these relationships explicit. Some teachers used animations and simulations to focus on the particulate level but then never
connected the symbols in the reaction back to the macroscopic scale. There was evidence of teachers lacking in this component of TSPCK. When questioned, many could not provide examples of activities to develop these concepts or stated that in lieu of utilizing them they allocated more time towards final assessment practice.

Teachers were able to identify misconceptions that were typically elicited via open-ended questions on the final exam. However, many were not aware of misconceptions that extended beyond this limited scope that have been identified in chemistry education research. None of the subjects reported misconceptions related to cell potentials. As the pre-test indicated, the students’ first exposure to electrochemistry was through classroom instruction, and thus it seems a missed opportunity to remedy these misconceptions. The teachers demonstrated considerable knowledge of misconceptions on topics within the curriculum; however, they lacked knowledge of misconceptions not explicitly covered in the curriculum.

All teachers at some point throughout the study reported that electrochemistry was a challenging unit for their students, yet they were only able to identify one or two areas within the topic as difficult to teach. With claims that the curriculum is challenging and there is a demanding timeframe for high stakes exam preparation, this assertion seems counterintuitive. The responses tended to indicate teachers believed the topic is difficult mainly due to student related causes rather than as a result of a weakness in their pedagogy. For example, teachers often cited student struggles as opposed to “teacher centric” reasons such as “I have a difficult time…” Furthermore, the responses were often in terms of incorrect test responses as opposed to what they found difficult to present to students.

**Teaching methodologies.** Overall, subjects as a whole scored highest in this domain of TSPCK. Teachers had a ‘toolkit’ of strategies in their general PCK that they have adapted and successfully implemented in the electrochemistry unit. One noticeable deficiency in TSPCK was a lack of demonstrations and/or activities or laboratories related to teaching electrolytic cells. Many teachers omitted hands-on activities due to the placement of the topic towards the end of the curriculum, while others wanted to spend more time on test preparation and some simply were not aware of an activity they could utilize. While most teachers discussed the importance of teaching electrochemistry to provide science applications in the real world, they missed the opportunity to engage learners through the application of electrolytic cells by means such as electrolysis, hydrolysis, or plating. All teachers had demonstrations, activities and/or labs to help their students learn about voltaic cells. The subjects did not choose the same demonstrations or activities in general, but as a whole subject group seemed most well versed in this area of TSPCK.

**General findings.** The assessment and interview data provided evidence of teacher strengths and weaknesses in TSPCK in the area of electrochemistry. The most significant factor in TSPCK composite score was the level of course taught. Teachers who taught a variety of student levels such as introductory, Regents and AP levels demonstrated higher TSPCK. This suggests that it might be beneficial for all teachers to teach higher-level students, perhaps on a rotating basis to keep their content knowledge up to date. Additionally, teaching standard and lower level courses and students with varying levels of academic abilities is a beneficial experience as it requires teachers to address misconceptions from the most basic to the most complex. Moreover, only teaching AP and advanced chemistry students is not sufficient for adequate TSPCK development, as teachers’ skills and strategies often do not incorporate learning difficulties in
basic concepts. Finally, higher TSPCK did not correlate to high student learning gains, as student learning is affected by many factors such as SES.

Teachers were asked to look at models of voltaic and electrolytic cells and discuss the models’ strengths and weaknesses. One model used in the TSPCK exam comes from Huddle and White (2000), which was described previously in the literature review. None of the teachers in this study were aware of the model, despite the fact that the participants expressed an interest in learning more about potential models for instruction of electrochemistry. The model provided a macroscopic concrete method of teaching voltaic cells that addressed many of the common misconceptions during instruction of the unit. Teachers were aware the subject is difficult to learn, yet did not view science education research as a worthwhile source to consult. Teachers’ lack of knowledge about this specific model does not necessarily mean their TSPCK was limited, however, it would be worth examining through an in-service workshop ways for experienced chemistry teachers to incorporate research-based models into their instruction.

This section summarizes the main findings of the study of electrochemistry TSPCK of eight experienced chemistry teachers. The teachers failed to provide explicit evidence for TSPCK in electrolytic cells, in particular when designing activities and/or demonstrations to have students observe electrolytic cells on a macroscopic level. The misconceptions and real life examples teachers were able to provide were mostly derived from exam questions. Teachers who continuously teach a Regents curriculum were focused on ensuring their students were successful on the culminating high stakes test. Motivation for curricular extensions was not a priority when students’ test scores were the measure of teacher effectiveness. Thus, a consequence of high stakes testing as evidenced by this study is limiting TSPCK development of the chemistry teachers. Additionally, teachers in high SES districts may have been unaware that their TSPCK was lacking because their students were still successful. Additionally, teachers in high SES districts may be unaware that their TSPCK is lacking because in spite of it, their students are still successful. Moreover, with TSPCK having a small effect on high SES student performance, it is no wonder that states are allowing the creation of teacher academies in order to fast-track teachers to classroom, without adequate TSPCK training.

5.2 Implications

This section addresses implications that can be derived from the results of this study. This section will first discuss the implications regarding assessment and curriculum. Professional development implications for in-service teaches will follow. Lastly, implications for pre-service training will be discussed.

Curriculum and assessment. The current educational system in NYS does not assess teachers in their TSPCK, and their proficiency may not progress as long as overall student performance meets current guidelines. Teachers can lack TSPCK in a particular topic, but still possess sufficient general PCK to guide students towards success on the final exam. The means by which teachers are assessed needs to be adapted to show teacher proficiency in all topics within the curriculum.

Another implication of this study is that a teacher’s TSPCK becomes limited by the nature of the final assessment. There are unintended consequences of high-stakes tests in that they diminish the depth of knowledge for both the teacher and the student. Teachers are willing to
spend a significant amount of time on review, in some cases weeks of the course, to get the students prepped for final assessment rather than exploring topics in more depth.

Finally, only two of the teachers in this study were chemistry majors as undergraduates and only three teachers had taken a physical chemistry courses in college. All teachers completed general chemistry and organic coursework. Barbara neither majored in chemistry nor had she taken a course in physical chemistry but exhibited exemplary TSPCK. One implication from this is that teachers who are deficient in content area training but learn the curriculum for a higher level course such as AP or IB chemistry may overcome this deficiency in preparation. The teachers were taught electrochemistry in their general chemistry coursework; since there was not significant electrochemistry knowledge assessed on the Regents exam, the general chemistry coursework may have been sufficient. However, if new teachers were required to teach AP or IB chemistry, studying the additional chemistry content could provide a source of enrichment necessary for the teacher to develop more sophisticated TSPCK.

**Professional development.** Professional development for current chemistry teachers needs to be improved to develop the pedagogy of those who influence students to enter and persist in the STEM pipeline. The teachers in this study introduced applications of electrochemistry to students sparsely. Most teachers were only able to list two applications of electrochemistry, which were typically the same ones on the final assessment. Moreover, only one teacher incorporated a lab on electrochemistry. These teachers were limited in their time and ability to enhance electrochemistry learning via hands on activities. Teachers need professional development to show applications and real life examples to support their students. Students may be less willing to pursue a STEM major without experiencing hands-on application of the content.

Teachers who taught multiple levels of chemistry, including AP Chemistry, scored highest in TSPCK in electrochemistry. Teaching a variety of levels of chemistry is beneficial in TSPCK development. Teachers reported they were not able to find TSPCK professional development, which limited their ability to acquire new skills. Most teachers stated that content specific professional development was difficult to find and they might be interested in taking a TSPCK course if one were available. It is unfortunate that teachers were not utilizing the science research available to improve their TSPCK of various topics, not just electrochemistry. There exists a large disconnect between science education research and high school teachers who stand to benefit.

**Teacher preparation.** In the area of teacher preparation, teachers reported they received insufficient TSPCK training. Since TSPCK develops over time, if its foundation is not established at the pre-service level, there is no evidence it will develop once the teacher enters the profession. Teacher preparation programs are producing teachers who may exhibit sufficient content knowledge and pedagogical knowledge as deemed by certification exams, but TSPCK may be deficient in certain areas.

While content knowledge is necessary for TSPCK transformation, the results of this study showed that teachers, who took advanced electrochemistry, by means of a college physical chemistry course, did not necessarily have greater TSPCK. Margene, Joey and Benjamin all took physical chemistry courses in college and ranged in their TSPCK composite scores. Margene has exceptional TSPCK but Joey and Benjamin were proficient. While other teachers such as Alby and Barbara may have had deficiencies in coursework, teaching varying levels of chemistry
mitigated this and allowed them to show exemplary TSPCK in spite of not having taken a formal undergraduate physical chemistry course.

5.3 Recommendations

The results of this study suggest the need for curricular and testing overhaul. Teacher evaluation systems need to be revised to improve student learning. To help current teachers who may lack TSPCK, professional development opportunities need to be made available to assist teachers in TSPCK growth. In addition, the means by which teachers are trained should be altered to include explicit TSPCK training. The next section will describe recommendations for TSPCK development and improvement through changes to state assessments and curriculum, followed by recommendations for in-service teachers and concluding with teacher preparation.

Curriculum and assessment. Chemistry education in NYS has become extremely focused on high stakes tests. The reality of high stakes testing to evaluate teacher success is an education system where teachers are forced to “drill and kill” students on practice assessment questions to demonstrate understanding of the content. If teachers’ success must be tied to a score on a high stakes test, the means by which students are evaluated needs to be changed. The motivation for teachers to develop lessons focused on constructivist learning may be diminished as they encounter tensions between their desire to teach with best practices and their requirement to teach in compliance with what will be assessed on the tests. Assessments need to be amended to meet the needs of 21st century learners who engage in critical thinking.

During the survey only two of the teachers used a pre-assessment to probe the students to determine if they had any knowledge of the subject. Many of the teachers did not incorporate a pre-assessment into their instruction. The teachers’ agenda was so focused on what they needed to teach to prepare the students for the state test that uncovering or discussing misconceptions did not seem important to them. Research has supported using data from pre-assessments to drive or alter instruction, and despite these experienced teachers knowing this or saying they should do it, the value added was not enough of an incentive. Again, this suggests the need for a new exam that is not focused on rote memory but requires students to think critically about chemistry principles and phenomena. If the structure of the exam changes, teachers will be forced to change instruction to address the style of learning being assessed. Additionally, the curriculum needs to change in order to be less reliant on rote memory and allow more time for inquiry and conceptual learning.

Professional development. Teaching, like all professions, is fluid and dynamic. State teaching requirements for professional development need to be amended to require teachers to continually learn and grow in their field. Teachers are not required to engage in content specific professional development and this is limiting their development of TSPCK. All subjects indicated they had not received content specific professional development in electrochemistry. Perhaps the reason why no electrolytic activities were incorporated was that the teachers had never learned them in pre-service or in-service training. While there have been many developments in this area of chemistry education research, many high school teachers who could have benefited from this work were not exposed to it and thus did not benefit from its insights. Large-scale dissemination of research-based electrochemistry instructional materials is recommended to improve student understanding.
The current system does not provide incentives for teachers to develop their TSPCK within their content areas. A recommendation would be to create a system whereby teachers are evaluated and provided constructive feedback to allow them to develop their TSPCK and adjust their instruction. To a building principal or even administrator who is not certified in the content area, providing insights into different labs, simulations, and discipline specific methods of teaching cannot occur, as the content knowledge is just not there. The need for content specific evaluators, perhaps in the form of professional learning committees who assume the role within buildings, districts or regions could provide the curricular support necessary for TSPCK growth.

TSPCK in-service training should be provided in the form of workshops focused on particular topics. Additionally, teachers could complete TSPCK modules where they learn about the components of TSPCK for a particular unit and then demonstrate competency in that topic. Another recommendation would be for the state to mandate that teachers complete tasks, modules or TSPCK exams as a part of maintaining certification. Finally, content specific professional development that incorporates chemistry education research should be offered.

An additional suggestion for professional improvement would be to mandate different types of professional development for teachers. The type of professional development reported least by the teachers was that of scientific investigations. A recommendation would be for state colleges to serve as hubs for teacher resources and professional learning communities. This could be achieved by the state funding a teacher support center to provide them with opportunities to meet their pedagogical needs.

**Teacher preparation.** Teacher preparation needs to be modified to meet the needs of current teachers. A recommendation is the implementation of TSPCK coursework for pre-service teachers. Teachers are traditionally taught chemistry content in their subject area coursework and then proper pedagogy in their education coursework. Newly designed courses are needed to instruct teachers specifically on how to teach sub-disciplinary chemistry topics effectively. Most teachers suggested this type of course would be worth taking even though they had many years of experience. The problem is these courses are not commonly taught, despite the positive results experienced in the physics teacher preparation program at Rutgers University with offering such courses to pre-service teachers. Rutgers requires fifteen credits devoted to PCK development so teachers are presented misconceptions and teaching methodologies to address every area of the physics curriculum. A similar model should be created to allow for sufficient teacher preparation in the chemistry field. Additionally, the Rutgers program has created a professional network whereby teachers who graduate support student teachers in the program.

An alternate means of increasing TSPCK instruction at the pre-service level would be to require teachers to complete TSPCK tasks or assessments prior to exiting the program. Another method would be the completion of modules for each topic to demonstrate competency in the TSPCK. Additionally, in regards to obtaining certification, TSPCK exams should be required as opposed to content and pedagogy exams taken separately.

**5.4 Future Research**

PCK is difficult to assess due to its complexity and abstract nature. The TSPCK exam and interview tasks may be a more effective means of evaluating teacher competency in a particular discipline than a content knowledge exam. Teachers entering the profession may show competency via a content exam; however, strong content knowledge does not necessarily correlate with the ability to successfully impart that knowledge in a way that is comprehensible.
for students. Further research should evaluate teacher preparation programs that emphasize TSPCK development on a large scale with measured student outcomes over several years. TSPCK competency should be measured prior to entering the field as well as through exploration of its effects on teacher retention and confidence.

Similarly, research should explore the TSPCK development of teachers who stay niched in a professional learning community compared to those who do not, in order to examine how TSPCK changes over time for groups of teachers. Additionally, student achievement in this study was moderately correlated with the SES of the student population, irrespective of the TSPCK of the classroom teacher. A comparison among teachers in this sample who participated in a professional learning community and evidenced a high level of TSPCK to teachers from outside of that learning community that work with students with the same SES could be informative. A future study could explore whether TSPCK composites were correlated with students learning outcomes of the same SES and if so which components of TSPCK were most significant. Follow-up research utilizing exploratory sequential design could use the results of this qualitative study to inform a randomized, controlled quantitative study of teacher TSPCK (Creswell, 2012).

Also, research should examine how TSPCK develops as a result of professional development opportunities for in-service teachers. If experienced teachers are deficient in their knowledge of electrochemistry, they may be deficient in other areas of the curriculum. Further studies should examine the best means of supporting TSPCK development in experienced teachers via tasks, exams, modules, and workshops to determine which types of strategies show the greatest benefit to teachers and their students.

Lastly, research needs to evaluate the impact of science education research on high school educators. Teachers wanted more professional development, but reading journal articles seemed to be the least common approach taken to grow in their practice. How best can the gap between research and practice be bridged? Mechanisms for disseminating chemistry education research to teachers is necessary since they are key stakeholders who have the greatest opportunity to improve student learning and enthusiasm for chemistry.
References


Appendix A: Student Redox Pre- and Post-Assessment

1. The chemical process in which electrons are gained by an atom or an ion is called
   A) addition  B) oxidation  C) reduction  D) substitution

2. Which ion is most easily reduced?
   A) Zn^{2+}  B) Mg^{2+}  C) Co^{2+}  D) Ca^{2+}

3. Given the balanced ionic equation:
   \[ 2\text{Al}(s) + 3\text{Cu}^{2+}(aq) \rightarrow 2\text{Al}^{3+}(aq) + 3\text{Cu}(s) \]
   Compared to the total charge of the reactants, the total charge of the products is
   A) less  B) greater  C) the same

4. A student collects the materials and equipment below to construct a voltaic cell:
   - two 250-mL beakers
   - wire and a switch
   - one strip of magnesium
   - one strip of copper
   - 125 mL of 0.20 M Mg(NO_3)_2(aq)
   - 125 mL of 0.20 M Cu(NO_3)_2(aq)
   Which additional item is required for the construction of the voltaic cell?
   A) an anode  B) a battery  C) a cathode  D) a salt bridge

5. What occurs at one of the electrodes in both an electrolytic cell and a voltaic cell?
   A) Oxidation occurs as electrons are gained at the cathode.
   B) Oxidation occurs as electrons are lost at the anode.
   C) Reduction occurs as electrons are gained at the anode.
   D) Reduction occurs as electrons are lost at the cathode.

6. Which energy conversion must occur in an operating electrolytic cell?
   A) electrical energy to chemical energy  B) electrical energy to nuclear energy
   C) chemical energy to electrical energy  D) chemical energy to nuclear energy

7. Which ionic equation is balanced?
   A) \( \text{Fe}^{3+} + \text{Al} \rightarrow \text{Fe}^{2+} + \text{Al}^{3+} \)
   B) \( \text{Fe}^{3+} + 3\text{Al} \rightarrow \text{Fe}^{2+} + 3\text{Al}^{3+} \)
   C) \( 3\text{Fe}^{2+} + \text{Al} \rightarrow 3\text{Fe}^{2+} + \text{Al}^{3+} \)
   D) \( 3\text{Fe}^{3+} + \text{Al} \rightarrow \text{Fe}^{2+} + 3\text{Al}^{3+} \)

8. Which reaction occurs spontaneously?
   A) \( \text{Cl}_2(g) + 2\text{NaBr}(aq) \rightarrow \text{Br}_2(l) + 2\text{NaCl}(aq) \)
   B) \( \text{Cl}_2(g) + 2\text{NaF}(aq) \rightarrow 2\text{F}_2(g) + 2\text{NaCl}(aq) \)
   C) \( \text{I}_2(s) + 2\text{NaBr}(aq) \rightarrow \text{Br}_2(l) + 2\text{NaI}(aq) \)
   D) \( \text{I}_2(s) + 2\text{NaF}(aq) \rightarrow 2\text{F}_2(g) + 2\text{NaI}(aq) \)

9. What is the oxidation number of manganese in \( \text{KMnO}_4 \)?
   A) +7  B) +2  C) +3  D) +4
10. Which balanced equation represents a redox reaction?
   A) AgNO₃(aq) + NaCl(aq) → AgCl(s) + NaNO₃(aq)
   B) H₂CO₃(aq) → H₂O(l) + CO₂(g)
   C) NaOH(aq) + HCl(aq) → NaCl(aq) + H₂O(l)
   D) Mg(s) + 2HCl(aq) → MgCl₂(aq) + H₂(g)

11. Given the reaction:
    \[ 2 \text{Al}(s) + \text{Fe}_2\text{O}_3(s) \xrightarrow{\text{heat}} \text{Al}_2\text{O}_3(s) + 2 \text{Fe}(s) \]
    Which species undergoes reduction?
    A) Al
    B) Fe
    C) Al³⁺
    D) Fe⁺³

12. Given the reaction:
    \[ \text{Zn}(s) + 2 \text{HCl}(aq) → \text{ZnCl}_2(aq) + \text{H}_2(g) \]
    Which statement correctly describes what occurs when this reaction takes place in a closed system?
    A) Atoms of \text{Zn}(s) lose electrons and are oxidized.
    B) Atoms of \text{Zn}(s) gain electrons and are reduced.
    C) There is a net loss of mass.
    D) There is a net gain of mass.

13. Given the balanced equation representing a reaction occurring in an electrolytic cell:
    \[ 2\text{NaCl}(\ell) → 2\text{Na}(\ell) + \text{Cl}_2(g) \]
    Where is \text{Na}(\ell) produced in the cell?
    A) at the anode, where oxidation occurs
    B) at the anode, where reduction occurs
    C) at the cathode, where oxidation occurs
    D) at the cathode, where reduction occurs

14. The diagram below shows a key being plated with copper in an electrolytic cell

   ![Diagram of an electrolytic cell with a copper sulfate solution, battery, and copper electrode.]

   Given the reduction reaction for this cell:
   \[ \text{Cu}^{2+}(aq) + 2e^- → \text{Cu}(s) \]

   This reduction occurs at
   A) \(A\), which is the anode
   B) \(A\), which is the cathode
   C) \(B\), which is the anode
   D) \(B\), which is the cathode
15. Which energy transformation occurs when an electrolytic cell is in operation?
   A) chemical energy → electrical energy  
   B) electrical energy → chemical energy  
   C) light energy → heat energy  
   D) light energy → chemical energy  

Base your answers to questions 16 through 19 on the information below.

In a laboratory investigation, a student constructs a voltaic cell with iron and copper electrodes. Another student constructs a voltaic cell with zinc and iron electrodes. Testing the cells during operation enables the students to write the balanced ionic equations below.

Cell with iron and copper electrodes: \( \text{Cu}^{2+}(aq) + \text{Fe}(s) \rightarrow \text{Cu}(s) + \text{Fe}^{2+}(aq) \)

Cell with zinc and iron electrodes: \( \text{Fe}^{2+}(aq) + \text{Zn}(s) \rightarrow \text{Fe}(s) + \text{Zn}^{2+}(aq) \)

16. State the relative activity of the three metals used in these two voltaic cells.

17. Write a balanced half-reaction equation for the reduction that takes place in the cell with zinc and iron electrodes.

18. Identify the particles transferred between \( \text{Fe}^{2+} \) and \( \text{Zn} \) during the reaction in the cell with zinc and iron electrodes.

19. State evidence from the balanced equation for the cell with iron and copper electrodes that indicates the reaction in the cell is an oxidation-reduction reaction.
Base your answers to questions 20 and 21 on the information below.

A voltaic cell with magnesium and copper electrodes is shown in the diagram below. The copper electrode has a mass of 15.0 grams.

\[
\text{Mg(s) + Cu}^{2+}(\text{aq}) \rightarrow \text{Mg}^{2+}(\text{aq}) + \text{Cu(s)}
\]

When the switch is closed, the reaction in the cell begins. The balanced ionic equation for the reaction in the cell is shown below the cell diagram. After several hours, the copper electrode is removed, rinsed with water, and dried. At this time, the mass of the copper electrode is greater than 15.0 grams.

20. Explain, in terms of copper ions and copper atoms, why the mass of the copper electrode increases as the cell operates. Your response must include information about both copper ions and copper atoms.

21. State the purpose of the salt bridge in this cell.
22. Base your answer to the following question on the information below and on your knowledge of chemistry.

In a laboratory apparatus, a sample of lead(II) oxide reacts with hydrogen gas at high temperature. The products of this reaction are liquid lead and water vapor. As the reaction proceeds, water vapor and excess hydrogen gas leave the glass tube. The diagram and balanced equation below represent this reaction.

\[
\text{PbO(s) + H}_2\text{(g) + heat} \rightarrow \text{Pb(l) + H}_2\text{O(g)}
\]

Determine the change in oxidation number for the hydrogen that reacts.
Base your answers to questions 23 through 25 on the information below.

A student constructs an electrochemical cell during a laboratory investigation. When the switch is closed, electrons flow through the external circuit. The diagram and equation below represent this cell and the reaction that occurs.

\[
2\text{Al(s)} + 3\text{Ni}^{2+}(aq) \rightarrow 2\text{Al}^{3+}(aq) + 3\text{Ni(s)}
\]

23. Determine the number of moles of Al(s) needed to completely react with 9.0 moles of Ni\(^{2+}\)(aq) ions.

24. Write a balanced half-reaction equation for the oxidation that occurs when the switch is closed.

25. State the direction of electron flow through the wire when the switch is closed.
Appendix B: Horizon Instrument on Background and Beliefs

Q1 Research participant
Q2 Age:
Q3 School district in which you are currently employed:
Q4 List how many years have you taught (including this year)
   any subject at the K-12 level (1)
   high school chemistry (2)
   in your current school (3)
Q5 At which college/university did you obtain the following?

<table>
<thead>
<tr>
<th></th>
<th>University/college (1)</th>
<th>Area of study (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bachelors Degree (1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Masters Degree (2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post Masters (3)</td>
<td></td>
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</tbody>
</table>

Q6 What is your primary area of certification?
Q7 What additional certifications do you hold?
Q8 Which of the following best describes your pathway to becoming a teacher?
   ☑ An undergraduate program leading to a bachelors’ degree and a teaching credential (1)
   ☑ A master’s program that also awarded a teaching credential (2)
   ☑ A post-baccalaureate credentialing program (no master’s degree awarded) (3)
   ☑ Other (4)

Q9 When did you last participate in professional development focused on chemistry teaching?
   (Include attendance at professional meetings, workshops, and conferences, as well as professional learning communities/lesson studies/teacher study groups. Do not include formal courses for which you received college credit or time you spent providing professional development for other teachers.) Check which applies:
   ☑ In the last 3 years (1)
   ☑ 4-6 years ago (2)
   ☑ 7 – 10 years ago (3)
   ☑ More than 10 years (4)
   ☑ Never (5)

Q10 What is the total amount of time you have spent on professional development in chemistry or science teaching in the last 3 years? (Include attendance at professional meetings, workshops, and conferences, as well as professional learning communities/lesson studies/teacher study groups. Do not include formal courses for which you received college credit or time you spent providing professional development for other teachers.)
   ☑ Less than 6 hours (1)
   ☑ 6-15 hours (2)
   ☑ 16-35 hours (3)
   ☑ More than 35 hours (4)

Q11 Thinking about all of your chemistry related professional development in the last 3 years, to what extent does each of the following describe your experience? Check all that apply:
   ☑ Attended a workshop on science or science teaching (1)
- Attended a national, state, or regional science teacher association meeting/conference (2)
- Participated in a professional learning community/lesson study/teacher study group focused on science or science teaching? (3)
- Other (4)

Q12 Thinking about all of your chemistry related professional development in the last 3 years, to what extent does each of the following describe your experience (1 being not at all, 3 somewhat and 5 to a great extent):
- You had opportunities to engage in science investigations (1)
- You had opportunities to examine classroom artifacts (for example: student work samples). (2)
- You had opportunities to try out what you learned in your classroom and then talk about it as part of the professional development. (3)
- You worked closely with other science teachers from your school. (4)
- You worked closely with other science teachers who taught the same grade and/or subject whether or not they were from your school. (5)

Q13 Are you able to readily find professional development opportunities focused on improving your chemistry instruction?
- Yes (1)
- No (2)

Q14 If you were interested in attending a chemistry workshop or conference, would your district provide funding?
- Yes (1)
- No (2)
- Part of the cost would be covered (3)

Q15 When did you last take a formal course for college or graduate credit in each of the following areas?

<table>
<thead>
<tr>
<th>Course Type</th>
<th>In the last 3 years (1)</th>
<th>4-6 years ago (2)</th>
<th>7-10 years ago (3)</th>
<th>More than 10 years ago (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemistry content (1)</td>
<td></td>
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<tr>
<td>Pedagogy as it relates to chemistry (2)</td>
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<tr>
<td>Science content other than chemistry (3)</td>
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<tr>
<td>Pedagogy in general (4)</td>
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<td>Other (5)</td>
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Q16 Colleges typically offer teacher preparation courses that group all high school science instruction together. For example physics, chemistry, biology, and earth science teachers are combined in one class. Have you ever taken a class that was specifically designed to provide pedagogical content knowledge (PCK) for chemistry teachers? PCK in chemistry includes knowledge of curriculum, knowledge of student misconceptions, and teaching methodologies for
transforming your chemistry content knowledge into instruction via analogies, representations, and the means that address student misconceptions.

- Yes (1)
- No (2)

Q17 At this point in your career, would you be interested in taking a college course in pedagogical content knowledge (PCK)?
- Yes (1)
- No (2)

Q18 In the past three years have you:

<table>
<thead>
<tr>
<th>Question</th>
<th>Yes (1)</th>
<th>No (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Received feedback about your science teaching from a mentor/coach formally assigned by the school or district? (1)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Served as a formally assigned mentor/coach for science teaching? (Please do not include supervision of student teachers.) (2)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Supervised a student teacher in your classroom? (3)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Taught in-service workshops on science or science teaching? (4)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Led a professional learning community/lesson study/teacher study group focused on science or science teaching? (5)</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

Q19 Please fill in the following regarding your current teaching load.

<table>
<thead>
<tr>
<th>Course</th>
<th>How many periods a week does the course meet (1)</th>
<th>Number of sections (2)</th>
<th>Average number of students per section (3)</th>
<th>Grade level of students enrolled (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regents Chemistry (1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP Chemistry (2)</td>
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</tr>
<tr>
<td>Non-regents chemistry (3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Science regents course other than chemistry (4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Science elective (5)</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Q20 How many periods do you devote to teaching oxidation, reduction and electrochemistry?
- 1 (1) through
- 25 (25)

Q21 How do you relay the content for this unit to the students?
- Traditional lecture (1)
- Flipped videos (2)
- Textbook readings (3)
- Other (4)

Q22 How well prepared do you feel to include each of the following as a part of your instruction on oxidation, reduction and electrochemistry? [Select one on each row (1- being not at all, 3- somewhat and 5- to a great extent)
Anticipate difficulties that students may have with particular science ideas and procedures in this unit (1)
Find out what students thought or already know about the key ideas in this unit (2)
Monitor student understanding during this unit (3)
Implement the curriculum for this unit (4)
Assess student understanding at the conclusion of this unit (5)

Q23 Which of the following did you utilize when you last taught the oxidation, reduction and electrochemistry unit? [Select all that apply.]

- Administered an assessment, task, or probe at the beginning of the unit to find out what students thought or already knew about the key science ideas (1)
- Questioned individual students during class activities to see if they were “getting it” (2)
- Used information from informal assessments of the entire class (for example: asking for a show of hands, thumbs up/thumbs down, clickers, exit tickets) to see if students were “getting it” (3)
- Reviewed student work (for example: homework, notebooks, journals, portfolios, projects) (4)
- Administered one or more quizzes and/or tests to see if students were “getting it” (5)
- Had students use rubrics to examine their own or their classmates’ work (6)
- Assigned grades to student work (for example: homework, notebooks, journals, portfolios, projects) (7)
- Administered one or more quizzes and/or tests to assign grades (8)
- Went over the correct answers to assignments, quizzes, and/or tests with the class as a whole (9)

Q24 Which of the following activities take place during your instruction of oxidation and reduction? [Select all that apply.]

- Teacher explaining a science idea to the whole class (1)
- Whole class discussion (2)
- Students completing textbook work (3)
- Students completing practice problems on worksheets (4)
- Students reading about science (5)
- Students using instructional technology (6)
- Teacher conducting a demonstration while students watched (7)
- Students doing hands-on/laboratory activities (8)
- Practicing for standardized tests (9)
- Test or quiz (10)
- Cooperative group (11)
- Other (12)
Appendix C: Topic Specific PCK Exam

Why do you think it is important for students to learn about electrochemistry?

What topics should have been covered in chemistry before you can teach electrochemistry. Please explain your rationale for each.

Reflecting on your experience of teaching redox and electrochemistry, what student misconceptions have you observed as common in this topic?

<table>
<thead>
<tr>
<th>Redox</th>
<th>Electrochemical Cells</th>
<th>Electrolytic Cells</th>
</tr>
</thead>
</table>

What concepts in electrochemistry do you believe are the main ideas for your students to understand by instruction on this topic? Choose at least three and place them in a sequence that you consider depicts an appropriate order of teaching. Provide reasons for both your choice and suggested sequence.

<table>
<thead>
<tr>
<th>Suggested Concepts and Sequence</th>
<th>Reasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td></td>
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<tr>
<td>2.</td>
<td></td>
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<tr>
<td>3.</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td></td>
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<tr>
<td>5.</td>
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</tr>
</tbody>
</table>

Make a concept map or a diagram showing how the topics chosen above link to subordinate concepts. Use linking words to connect your concepts.

Are there any concepts that you find difficult to teach in electrochemistry? Select your choice and provide reason(s) in the table below.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Why is it difficult to teach?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>
Do you use any analogies when teaching the topic? If so please describe some typical examples below:

What visual representations, diagrams, models, do you use when teaching electrochemistry?

Below are three representations for teaching the concept of electrochemical cells (galvanic and electrolytic cells).
<table>
<thead>
<tr>
<th>Model/ Representation</th>
<th>How could it be useful when teaching?</th>
<th>Students will struggle with this model because...</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
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<tr>
<td>2</td>
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<td>3</td>
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</tbody>
</table>

Do you incorporate any conceptual learning strategies/ activities when teaching electrochemistry? If so, please summarize them.

How would you respond to a learner who writes on a test: “The electrons flow through the salt bridge to keep the galvanic cell neutral.”

How would you answer a student who asks, “Why is it true that in both electrolytic and galvanic cells, oxidation always occurs at the anode and reduction always occurs at the cathode?”

Students are given the following problem on their Regents exams.

The students were asked to write a half-oxidation reaction for the equation above. The following responses from students were obtained:

<table>
<thead>
<tr>
<th>Student Response 1:</th>
<th>Student Response 2:</th>
<th>Student Response 3:</th>
<th>Student Response 4:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl⁺ + 2e → 2Cl⁻</td>
<td>Na⁺ + e → Na⁻</td>
<td>2Cl⁻ = Cl₂ + 2e</td>
<td>2Na⁺ - 2e → 2Na</td>
</tr>
<tr>
<td>Student Response</td>
<td>Explain how you would assist these learners to move towards a more scientific understanding.</td>
<td></td>
<td></td>
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<td>------------------</td>
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<td>4</td>
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</tbody>
</table>

What strategies do you use to assess students learning on electrochemistry. Please share below.

Thank you.
Appendix D: Topic Specific PCK Tasks

Tasks for Electrochemistry

1. You apply to a new position and part of the interview process requires you to provide a demo lesson. The director hiring you indicates that the hiring committee would like you to show a demonstration during your lesson to help the students understand the topics of redox and electrochemistry. He provides some of the following demos as suggestions and says you can choose from one of the following or your own.

   - Placing iron wool in copper (II) sulfate
   - Placing Zn and Cu in acid
   - Galvanic cell
   - Electrolytic Cell

   a. Which one would you choose?
b. Why would you choose that particular demo? What about it makes it a good demo?
c. Can you sketch what you mean?
d. What do you think students will find difficult about the demo?
e. Do you actually use this demo in the class or another one perhaps? What other demos do you do if any, what do they show?
f. What about this demo relates to the content of redox and electrochemistry?
g. When in your unit would be a good time to do utilize this demo? Beginning, middle, end of the unit?
h. You are told that the teacher, whose class you will be performing the demonstration lesson, will be calling you to discuss where she will be in the curriculum. What prior knowledge would you expect the students to have for your lesson that you can discuss with the teacher regarding her students, before you give the demo lesson? Why do they need this information, knowledge of electrons, ions, etc.
i. How do you introduce this unit, do you teach redox and then electrochemistry, meaning what order is the information introduced to the students?

2. You pose the following question to your class after teaching about voltaic cells, “If you were to shrink down as small as you want so that you could swim around inside the beakers, what do you think you will see?”

![Diagram of Voltaic Cell]

Copper
Salt Bridge
Zinc
a. Why do you think students would struggle with this question (what incorrect answers do you think they would provide)?
b. Why are the electrons going through the wire, and which direction?
c. How many ions do you think they would say?
d. What happens when it runs?
e. Do you think your students understand the simultaneous nature of redox reactions?
f. What about this do you think is difficult for your students to learn?
g. What type of learning strategies do you use when teaching about this topic?
h. Do you assess students’ understanding of this on both a macroscopic and microscopic level?
i. When do your students learn about ions and electrons?

3. Definition of the terms oxidation and reduction along with historical significance.

Base your answers to questions 83 through 85 on the information below and on your knowledge of chemistry.

Early scientists defined oxidation as a chemical reaction in which oxygen combined with another element to produce an oxide of the element. An example of oxidation based on this definition is the combustion of methane. This reaction is represented by the balanced equation below.

Equation 1: CH₄(g) + 2O₂(g) → CO₂(g) + 2H₂O(g)

The definition of oxidation has since been expanded to include many reactions that do not involve oxygen. An example of oxidation based on this expanded definition is the reaction between magnesium ribbon and powdered sulfur when heated in a crucible. This reaction is represented by the balanced equation below.

Equation 2: Mg(s) + S(s) → MgS(s)

83 State why early scientists classified the reaction represented by equation 1 as oxidation. [1]

a. How do you think your students would respond?
b. Do you think the multiple definitions for oxidation and reduction makes it hard for students to learn the topic?
c. Fill in the chart
d. How do you teach redox...do your students use the textbook, learn from your ppt notes, a video?
e. How do you develop your curriculum and ppts, etc. whatever they say? What sources do you use to create your lessons?

| Definition | Which do you utilize in teaching this topic and why? | Why and how do you teach it? | What problems do you anticipate students encounter with this particular definition? | What techniques do you use to help your students understand this definition? |
Oxidation is loss of electrons and reduction is gain of electrons.

Oxidation is gain of oxygen and reduction is loss of oxygen.

Oxidation is an increase in oxidation number and reduction is a decrease in oxidation number.

Oxidation is a loss of hydrogen. Reduction is a gain of hydrogen.

4. Your current director would like to see an inquiry type lesson on voltaic cells which will give them the opportunity to create their own voltaic cells. While being observed here are some of the questions that the student groups ask. Please share how do you respond to each student issue in the moment? You can stop and have a whole class discussion. Tell me what you would do if this was actually happening in your class.

   A) “Can you help us, we set up our cell using glucose as our electrolyte for the salt bridge and can’t get a voltage reading?”

   B) “We decided to create a lemon battery but don’t know what to use as the salt bridge.”

   C) “We used filter paper for the salt bridge and it’s not working, does it need to be wet and is there a certain length is must be?”

   D) “If we use the same metal for each electrode, will it still work?”

   E) “I don’t see anything happening, how do I know it’s actually working and conducting electricity?”

During the closing moments of the lesson, a student raises his hand and asks, “If you take a battery and put it in water would the water conduct electricity?
What do you do or say?
-What do you think the student would say?
5. This was question 47 on the August 2015 Regents chemistry exam.

Given the diagram representing an incomplete electrochemical cell:

- Wire
- Wire
- Carbon electrode
- CuCl₂(aq)
- Carbon electrode

Solid copper will be deposited on one of the carbon electrodes when the wires are connected to:

1. each other
2. a battery
3. a switch
4. a voltmeter

a. Your students are preparing for their final exam this year and they come across this as a practice question. Do you think this is a fair question?
b. What do you think the majority of your students would pick as the answer?
c. Why do you think students might struggle with this question?
d. What could you do to help your students answer this question?
e. How could you connect or relate this question to an idea/concept in real life?
f. As far a lab or activity how do you teach electrolytic cells?
g. Sketch set-up
Appendix E: Institutional Review Board Recruitment Letter and Consent

IRB Approved: 03/25/2015
Expiration Date: 03/24/2018
CORIHS Stony Brook University

Research Consent Form

Project Title: How is Pedagogical Content Knowledge (PCK) in the area of Oxidation and Reduction Manifested in High School Chemistry Teachers?

Principal Investigator: Angela M. Kelly, Ph.D.
Co-Investigators: Department: O'Brien, Stephanie, Ph.D. candidate
Center for Science & Mathematics Education

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

PURPOSE

The purpose of this study is:

The purpose of this study is to examine the varying methods by which chemistry teachers demonstrate chemistry content knowledge in the area of oxidation and reduction in a way that students find comprehensible. Teachers and their students will be evaluated on their content knowledge of oxidation and reduction to determine the extent to which the teachers were able to transfer their content to their students. School administrator approval to conduct the study will be obtained prior to the investigation. Teachers will be interviewed to uncover the methodologies for how the learning occurred within the classroom. The opportunity to find out how chemistry teachers transform their content knowledge into a form that is accessible to students is valuable. The results obtained from this study will provide useful information for science teacher educators to utilize in their programs of study to prepare more highly qualified teachers. This research also can be used to provide professional development to chemistry teachers. You are eligible for this study because you are a high school chemistry teacher in a Long Island school district. There will be approximately 10-20 participants in this study.

PROCEDURES

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

- A questionnaire regarding your demographic information, as well as information about your college education and professional development participation.
• A content inventory assessment (18 questions) in the area of oxidation and reduction.
• Your current students completing an assessment on oxidation and reduction.
• A 60 to 85 minute interview regarding your methodologies and strategies (PCK) you employ when teaching the topic of oxidation and reduction.
• Audiotaping of the interview, or if you prefer, the researchers will take field notes during the interview.

RISKS / DISCOMFORTS

The following risks/discomforts may occur as a result of you being in this study:

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

BENEFITS

• There is no direct benefit expected as a result of your participation in this study.

PAYMENT TO YOU

There is no payment for participation in this study.

CONFIDENTIALITY

Protecting Your Privacy in this Study

We will take steps to ensure that all the information we collect is kept private. Your name will not be used; we will use a code instead. All the study data that we collect will be kept in a locked cabinet. If any papers and talks are given about this research, your name and district will not be used. All audiotapes of interviews will be deleted after three years.

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

There is no cost for participation in this study.

YOUR RIGHTS AS A RESEARCH SUBJECT

- Your participation in this study is voluntary. You do not have to be in this study if you do not want to be.
- You have the right to change your mind and leave the study at any time without giving any reason, and without penalty.
- Any new information that may influence your decision to participate in this study will be given to you.
- You will get a copy of this consent form to keep. You do not lose any of your legal rights by signing this consent form.

QUESTIONS ABOUT THE STUDY OR YOUR RIGHTS AS A RESEARCH SUBJECT

- If you have any questions, concerns, or complaints about the study, you may contact Stephanie O’Brien, 73 1) 68 -6747, OR m.stephanie.obrien@gmail.com or Angela M. Kelly, Ph.D. (631) 632-1683.
- If you have any questions about your rights as a research subject or if you would like to obtain information or offer input, you may contact Ms. Judy Matuk, Committee on Research Involving Human Subjects, (631) 632-9036, OR by e-mail, judy.matuk@stonybrook.edu.

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

Will you allow the interview to be audiotaped: YES______ NO______

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

Subject Name (Printed) Subject Signature Date

Name of Person Obtaining Consent (printed) Signature of Person Obtaining Consent Date
Dear _____________________,

I am a doctoral student of Science Education at Stony Brook University and I plan to conduct a research study of the means by which chemistry teachers on Long Island are able to transform their content knowledge of oxidation and reduction into a form that is assessable to students. I hope to provide insights into how teachers’ knowledge of this topic can be improved upon through teacher preparation programs and professional development opportunities. Potential participants will include chemistry teachers who are currently teaching chemistry in a public school district on Long Island.

I am soliciting potential participants by contacting current chemistry teachers via email addresses that are publicly available and asking them to participate in a brief content assessment, a survey as well as a semi-structured interview. I am also requesting that a sample of your students complete a content assessment. Participants will be required to sign informed consent as a condition for participating in the study. Participants will also be required to obtain school administration consent. The identities of all participants and their schools and cities will be kept confidential. All interview transcripts will be destroyed three years after the study is completed.

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

Principal Investigator: Angela M. Kelly, Ph.D.
Co-Investigators: Department: O’Brien, Stephanie, Ph.D. candidate

If you have any questions, concerns, or complaints about the study, you may contact Stephanie O’Brien, (631) 678-6747, OR m.stephanie.obrien@gmail.com or Angela M. Kelly, Ph.D. (631) 632-1683

Thank you very much for your consideration.

Sincerely,

Stephanie M. O’Brien, Ph.D. Candidate

March 20, 2015