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# Assessing Student Understanding of the Visual Representation of the Voltaic Cell via the Three Phase Single Interview Technique

A Thesis submitted in partial satisfaction of the requirements for the degree Master of Science

in

Masters in Chemistry

by

Meng Yang Matthew Wu

Committee in charge:

Thomas Bussey, Chair
Stacey Brydges
Seth Cohen

2016

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The Thesis of Meng Yang Matthew Wu is approved and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego

2016

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# ACKNOWLEDGEMENTS

I would like to acknowledge Professor Thomas Bussey for his mentorship, the lack of which would have made this project not possible, and his support as the chair of my committee.  His guidance has been proven to be invaluable to my growth as a chemical education researcher.

I would also Professors Stacey Brydges, Christina Johnson, and Robert Pomeroy for their support; Jacqueline Wee for the creation of the voltaic cell representation shown to students during the interview; James Si for being an external coder; and all of the student participants for their contributions to this study.

# ABSTRACT OF THE THESIS

# Assessing Student Understanding of the Visual Representation of the Voltaic Cell via the Three Phase Single Interview Technique

by

Meng Yang Matthew Wu

Masters of Science in Chemistry

University of California, San Diego, 2016

Thomas Bussey, Chair

External representations of voltaic cells are readily found in undergraduate general chemistry textbooks. Like much of chemistry, electrochemistry requires that students develop and demonstrate a robust understanding of the particulate nature of chemical interactions; however, the voltaic cell is predominantly depicted at the macroscopic and symbolic levels of representation. Within the chemical education community, it is widely accepted that all three levels of representation are required for a scientifically accurate construct of a given concept. Under the theoretical framework of variation theory, this study investigated the application of the Three Phase Single Interview Technique to explore students' prior knowledge, their understandings of a common representation of a voltaic cell, and the relative importance students assign to voltaic cell features. Data was primarily collected through student interviews and student drawings ($N = 12$) with three case studies utilizing eye tracking data. This thesis reports that visual representations help cue students to reprioritize certain features of the voltaic cell, resulting in student generated drawings that incorporate much greater macroscopic and symbolic representational features. However, a majority of the interviewed students, when cued to think at the submicroscopic level, omitted particulate features of the voltaic cells in their representations and displayed alternative conceptions with respect to electronic and ionic interactions. If instructors were to utilize external representations such as the voltaic cell, they must be purposeful in its portrayal, highlighting the overlap of the three levels of representation as well as critical features to effectively promote a scientifically acceptable conception among students.

# Chapter 1 Introduction

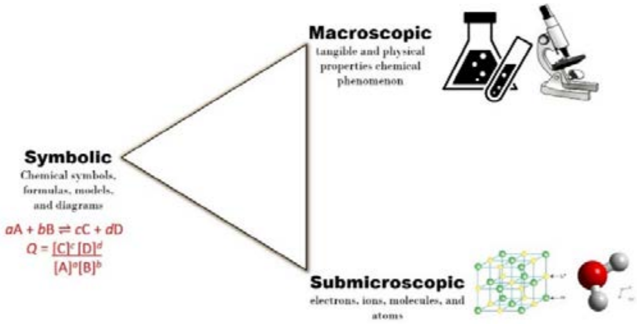
In science education, external representations (a systematic means of displaying information via a range of forms such as pictures, diagrams, and tables) have become widely used throughout the classroom setting to present instructional materials to help deepen student understanding of scientific concepts (Cook, 2006). With the advent of increasingly advanced multimedia technologies by the 21st century, teaching aids such as computer graphics, animations, and simulations have showcased the importance for students to process information via a range of visual mediums. As a previous study have shown, by providing a bridge between concrete and abstract representations, a large variety of external representations such as a 3D structure of a molecule have been well-received by students when tackling complex problems (Ferk, Vrtacnik, Blejec, & Gril, 2003). Furthermore, external representations such as a chemical diagram serve a variety of additional functions: making information more accessible, presenting visual cues, and facilitating students to predict, deduce, and hypothesize. When education is paired with exercises of interpreting and constructing chemical diagrams that are otherwise abstract during the instructional period, students show greater and consistent improvement (Davidowitz, Chittleborough, & Murray, 2010). Specifically, the use of representations such as a digital tool to build molecular models can deepen understanding of chemical concepts and thus help students accurately build mental models (Wu, 2001). Representations also benefit students by not only maintaining their attention and motivation but also promoting understanding that may not have occurred from reading strictly the text by itself. Shown in a study where college students were provided with simple illustrations paired with short captions, students were able to recall and solve meteorology problems equally or in some cases better than those who had full text by itself (Mayer, Bove, Bryman, Mars, & Tapangco, 1996). Thus, within the classroom setting, external representations serve as a powerful compliment to the already ubiquitous nature of text when conveying new information for knowledge acquisition.

Even outside the classroom, external representations have become indispensable among chemists as a means of facilitating communication. Countless representational examples such as thin later chromatography plates, structural diagrams, or gas chromatography plots within the scientific world are tools that enable scientists to communicate with their peers in their analysis of physical phenomena (Kozma, Chin, Russell, & Marx, 2000). External representations, with the immense amount of information that can be conveyed, almost serve as a pseudo-language which circumvents or lessens barriers of understanding within the scientific community. Chemistry as a result constantly involves the skillful attribution and interpretation of symbolism with respect to graphic objects (Hoffman & Laszlo, 1991). With visual aids utilized by every chemist, student and teacher alike, external representations have an undeniable presence in science education. Therefore, it is highly advised that the incorporation of external representations remain as an incumbent facet of teaching for effective learning to take place (Nyachwaya & Wood, 2014). Throughout this thesis, the terms *visual representations* and *representations* will be used interchangeably.

Nevertheless, the usage of representations can be challenging. To understand the difficulty that comes with external representations, one must examine the three levels in which representations are conveyed.

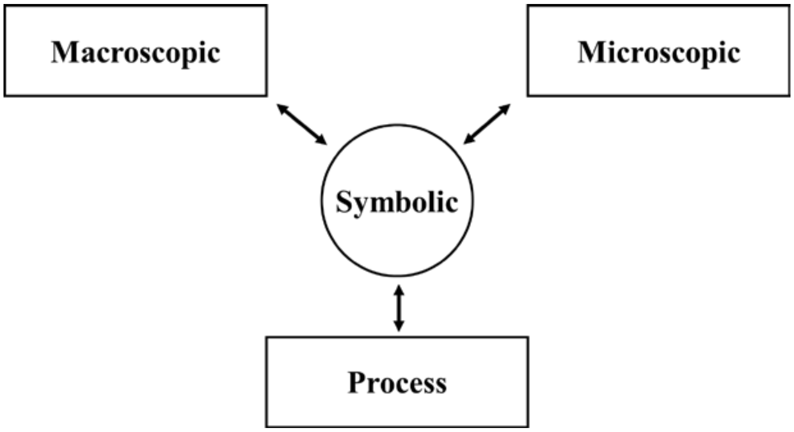
## Chapter 1.1 Johnstone's Three Levels of Representation

With respect to the representation's design, three levels are often utilized to describe a chemical phenomenon: the macroscopic, symbolic, and submicroscopic (Johnstone, 1982). The macroscopic level describes features that the viewer can physically interact with via sight, touch, or smell. The submicroscopic level conveys the particulate nature of the chemical world that is invisible to the naked eye such as atoms, molecules, and ions. In this thesis, the terms *submicroscopic* and particulate will be used interchangeably. Finally, the symbolic level encapsulates the words, letters, graphs, and equations that already have an affixed significance or meaning (Johnstone, 2000). In other words, the macro and submicroscopic levels provide theoretically descriptive and explanatory meaning respectively while the symbolic level serves as the technical vocabulary in which to convey the two (Taber, 2013). This triangle of representation can be perceived as a scale between the macroscopic and the submicroscopic in which students need to navigate through: from the experimental aspect to the unseen particulate nature of a given chemistry phenomenon. Ultimately, both of these can be translated to the symbolic level of representation, highlighting their overall interconnectedness (Scheme 1).



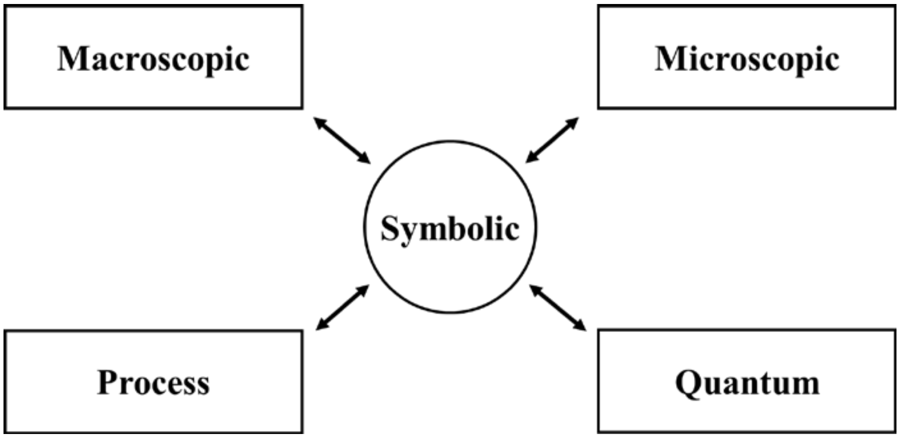
**Scheme 1**: Adaptation of Johnstone's Triangle of Representation

The relationship among these three levels existing as a “chemical knowledge triplet” has become paradigmatic in chemical education as a very popular framework that guides the work of textbook authors, instructors, and software developers (Talanquer, 2011). For example, the inclusion of animations in science learning has been demonstrated to be helpful with regards to student testing, concept retention and retrieval, or application because of how they convey dynamic visualizations of scientific processes such as molecular interactions or Newtonian physics (Cook, 2006; Sanger & Greenbowe, 2000; Rieber, 1990). As time progressed, Johnstone’s triangle of representation has been modified and re-conceptualized in a variety of ways. For example, a fourth level designated as the process level (Scheme 2) has been suggested where it describes the chemical process encapsulating a reaction in the context of the three existing levels (Dori & Hameiri, 2003).



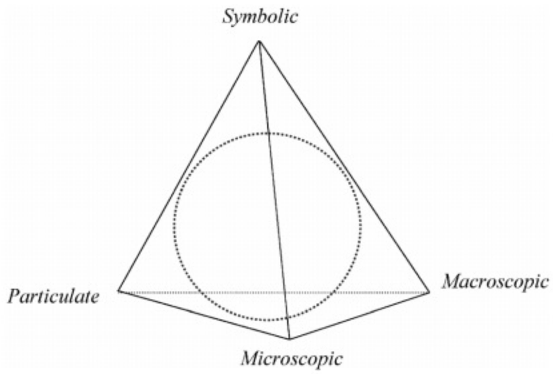
**Scheme 2:** Adapted Model of Four Levels of Representation (Dori & Hameiri, 2003)

Furthermore, additional research has modified the three levels by noting how representations synthesize elements from different levels to create hybrid, multiple, and mixed representations (Gkitzia, Salta, & Tzougraki, 2011). Within quantum mechanics, a fifth level has also been suggested to represent the quantum level (Scheme 3) which involves understanding electronic structures of atoms, molecules, and the solid state (Dangur, Avargil, Peskin, & Dori, 2014).



**Scheme 3**: Adapted Model of Five Levels of Representation (Dangur *et al.,* 2014)

In biochemistry, it has been suggested to adopt a biochemistry tetrahedron where each of the vertices represents symbolic, particulate, macroscopic, and microscopic domains respectively (Scheme 4).

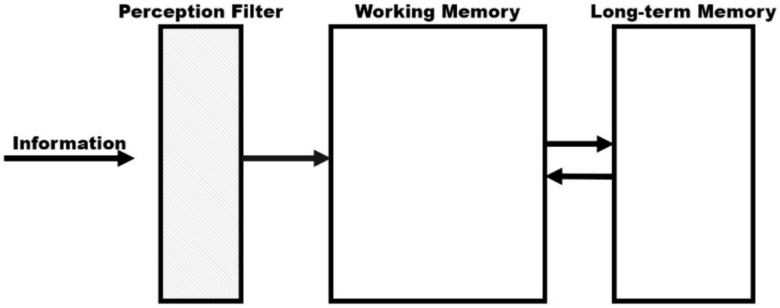


**Scheme 4:** Biochemistry Tetrahedron (Towns *et al*., 2012, p. 297)

In this adaptation, the microscopic domain refers to what can be seen under a microscope while the particulate domain refers to anything on the molecular level. This tetrahedron serves as a framework which allows researchers to discuss the utilization of external representations, the designing of studies, and curriculum development (Towns, Raker, Becker, Harle, & Sutcliffe, 2012). Despite the many iterations Johnstone's triangle of representation has experienced, the basic tenets set forth that underlie the significance of Johnstone's representational triangle have remained consistent throughout the years. Not only do students need to be exposed to all three levels but also they need to be able to comfortably transition and employ the three levels in their own rationalizations. (Johnstone, 2000). What this indicates is that understanding one or two of the three is simply not enough; there must be continuous cohesion among all three levels for effective understanding. Ultimately, generating a scientifically accurate understanding of chemistry, a discipline that is multi-representational by nature, requires students to cope with all three levels simultaneously; none of which are to be less significant than the other (Johnstone, 2009).

While representations can facilitate meaningful curriculum, there still exists the problem of the variance in their efficacy with regards to how students are learning and extrapolating the content. To assess the effectiveness of a representation, it is necessary to observe how students are responding via their interpretations of said representations (Pozzer-Ardenghi & Roth, 2005). When presented with multiple levels of representation, students oftentimes experience difficulty when making sense of the chemical concepts such how pressure cookers work, the functionality of a barometer, or why ice and steel ships float (Bodner, 1991). Faced with a large number of details, students can often experience cognitive load, a theory that focuses on the limited capacity of working memory that processes information (Sweller, Van Merriënboer, & Paas, 1998).

Working memory is a central theme when describing information-processing models in which it is generally accepted to be short-termed and limited in capacity (Baddeley, 2001). In order for information to be retained as long term memory (Scheme 5), an individual receives the information through a perception filter provided by the environment and process it in working memory first (Reid, 2008).



**Scheme 5:** Adapted Model of Information Processing (Cranford *et al.,* 2014)

As such, learning can be quickly hampered if instructional materials generate enough strain on a learner's working memory. Students can simply be overwhelmed with the amount of details presented to them. Too much presented information could lead to more details going unnoticed, thereby limiting student capacity to process new information and to connect to student prior knowledge (Cook, 2006). For example, when presented with the Lewis structure of acetic acid in a problem-solving exercise, a novice organic chemistry student could see the double bonds, the electron pairs, and the atoms as all separate components which constitutes as a quite high cognitive load. However, in the same problem-solving exercise an expert may view acetic in just two separate partitions: its carboxylic functional group and everything else.

Viewing this structure in clusters dramatically reduces the cognitive load and thus can be more effectively utilized when solving a problem (Cranford, Tiettmeyer, Chuprinko, Jordan, & Grove, 2014).

While the amount of information itself is a concern, the nature of the representational levels themselves can be challenging for students as well. Evinced by prior research, students typically have difficulty understanding the submicroscopic level because of its lack of relatability with physical experiences (Wu & Shah, 2004). As a result, students oftentimes focus primarily on the superficial features of the representation without tapping into the depth of their significance. Shown in a study involving animations with weather map changes, students tend to notice information when there is a dynamic contrast relative to the surrounding and ignore details that had low pictorial salience. In addition, the animation was ineffective in facilitating students to tap into subtleties of weather dynamics which sheds doubt on whether these concepts were properly retained and incorporated (Lowe, 2003). This study had shown that student understanding can be inhibited or skewed as a consequence of just retaining the macroscopic features while ignoring others. Furthermore, from the other side of the classroom setting, teachers throughout their curriculum would often discuss the three levels during instruction while omitting their interconnectedness, thereby limiting the overall image that students can conceptualize from representations (Gabel, 1999). Research has provided evidence that instruction which focuses on all three levels and their relationships with one another equally within the considerations of cognitive load theory can boost student performance. Students were shown to perform better in an examination when the interconnections of the three levels were highlighted, thereby underscoring the effectiveness of this teaching strategy (Milenković, Segedinac, & Hrin, 2014).

Another case that may negatively affect student learning is the lack of prior knowledge when viewing an external representation. Students lacking the adequate level of background knowledge may also have different interpretations of an external representation. The study had shown, in a comparison between the mental representations produced by meteorologists and non-meteorologists, that the former was more detailed while the latter was more general (Lowe, 1996). Thus, it was concluded that insufficient prior knowledge could restrain an individual's ability to create mental representations at the beginning stage of knowledge acquisition. What this shows is that despite how frequently external representations are used in science education, there exists a multitude of factors that enable students to experience external representation differently.

Thus, although representations have been demonstrated to be useful tools to promote understanding and communication, they be functionally ineffective if students are comprehending the representations in a limited or unintended manner. In addition, having to transition between the macroscopic and submicroscopic levels and then introducing the symbolic level that adds another level of transitioning can pose as a persistent challenge for students understanding chemistry concepts.

## Chapter 1.2 Constructivism

Effective teaching is commonly observed to not necessarily be proportionate to meaningful learning. Simply put, knowledge cannot be transferred as intact packages between teacher and student. The reason can be explained in a mantra-like phrase that has ingrained itself quite ubiquitously in the constant push to better understand learning: “Knowledge is constructed in the mind of the learner” (Bodner, 1986). Also known as the constructivist model, this theory of knowledge states that learners do more than just parrot what they hear or perceive; learners find meaning in the knowledge they obtain within the context of information they may possess (von Glasersfeld, 1984). What this signifies is that learners are constantly finding relevance in newly presented information within the contexts of their pre-established mental constructs of reality. As a result, the acquisition of knowledge is a persistent internal process in which learners assimilate and accommodate, two complementary processes in which the former involves fitting new information in currently existing mental frameworks and the latter involves readjusting pre-existing mental framework so as to rationalize new experiences (Smock, 1981). Meaningful learning cannot take place if information is simply disseminated to the learner; it needs to be an active mental process (Driver, 1988). In other words, learning has to be an active process in which new information is processed and mental constructs are readjusted accordingly. However, in such a process, the resultant mental construct simply needs to make sense to the individual for it to be maintained. Thus, constructivism helps explain how and why students are bringing a spectrum of alternative conceptions (i.e. misconceptions or naïve theories) into the classroom. For new knowledge to be internalized, it must first be related to prior knowledge the learner possesses (Ausubel, 1964). However, if prior knowledge consists of preconceived notions or alternative conceptions, the ability to learn may be impeded (Resnick, 1983). Oftentimes this would result in students adopting a conception that may work in their perspective of reality but may not be scientifically accurate. Thus, constructivism aims to elucidate the rationale behind why alternative conceptions are so impervious to instruction. Simply telling an individual he or she is incorrect is not enough to spur change; there needs to be an internal adjustment where the comparison of new and pre-existing theories effects contradiction (Niaz, 2002) and a revised, more appropriate theory is adopted (Bodner, 1986).

In terms of viewing external representations, students generate meaning through the lens of what they already know; and thus, students may pay attention to any number of particular features and come to any type of conclusions with respect to the external representation, regardless of its intended meaning. For example, the representation of the voltaic cell, a common representation found in almost every available chemistry textbook, is an external representation that chemistry students will encounter at some point of their learning experience. However, the representation of the voltaic cell may be difficult to interpret as it contains multiple levels being simultaneously displayed as well as a range of topics associated with electrochemistry. Such difficulty may lead students to interpret the representation of the voltaic cell in a variety of ways that may not be scientifically accurate, known as an *alternative conception*, *misconception*, or *naïve conception*. The term *alternative conception* will be utilized for the rest of this thesis.

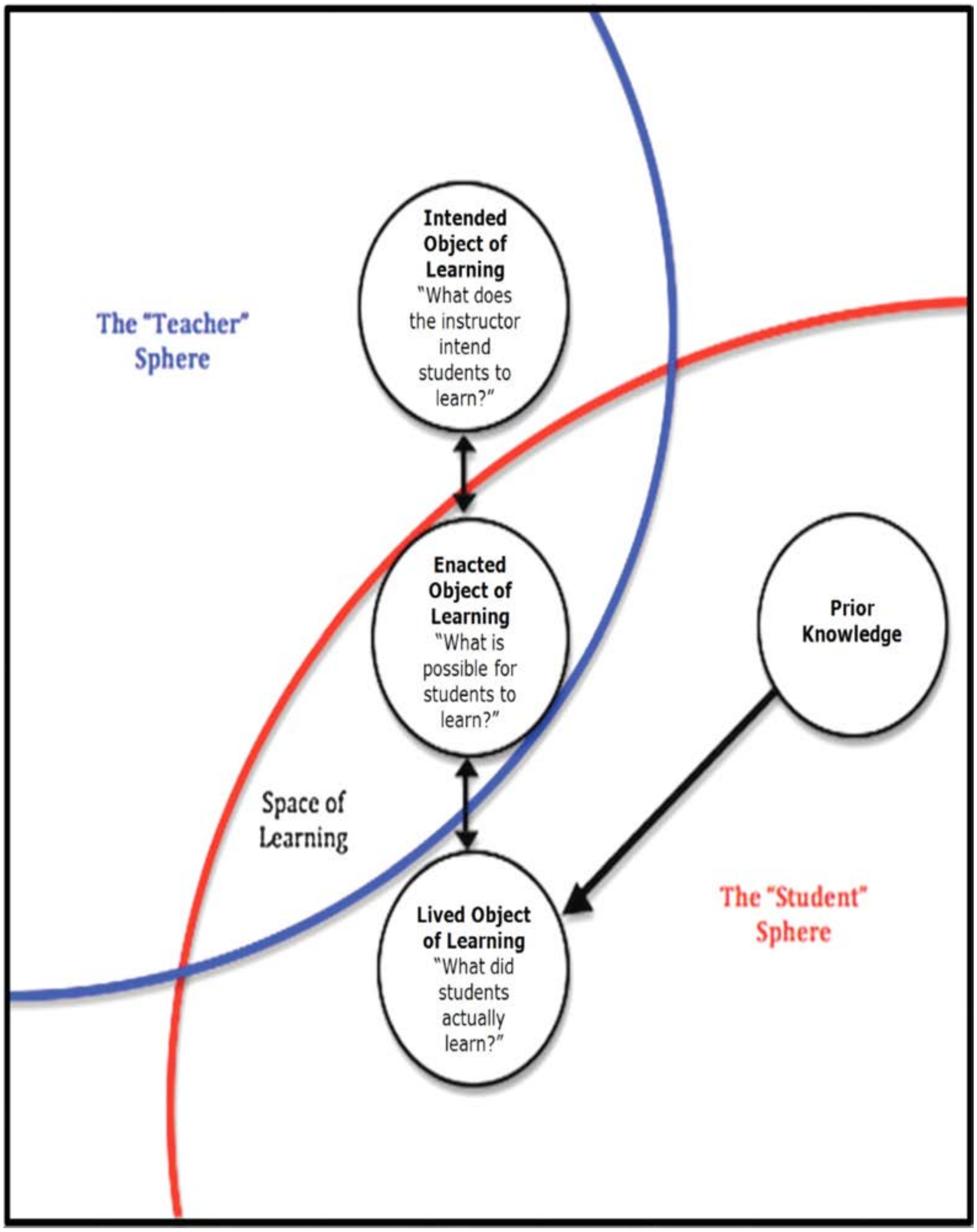
## Chapter 1.3 Alternative Conceptions within Electrochemistry

Throughout many instances of chemistry featured in the representation of the voltaic cell, students exhibit a multitude of alternative conceptions. For example, electron movement was believed to occur in solution, enabled by the attraction of present ions (Sanger & Greenbowe, 1997) and by piggybacking off of ions directly (Loh, Subramaniam, & Tan, 2014). Electrons were even theorized by students to move through the solution from the cathode, travel between the half cells via the salt bridge, and arrive at the anode in order to complete the circuit (Ceyhun & Karagölge, 2005). There was also reported difficulty in terms of students assessing the role of spectator ions in single-displacement redox reactions as well as both the application and understanding of charge and oxidation numbers (Brandriet & Bretz, 2014). With regards to the physical attributes of the cell itself, it had been reported that students believe that the identity of the cathode and anode depends on the half cells' physical placement and are unaware that half-cell potentials are intrinsic properties (Sanger & Greenbowe, 1999). Even instructors may potentially be under the guise of certain fallacies that they may unaware of; research had shown alternative conceptions with regards to standard cell potentials, electrochemical equilibrium, and chemical equilibrium (Özkaya, 2002). It is evident that the voltaic cell may be challenging for both students and teachers alike on the macroscopic, submicroscopic, and symbolic level. As a result, as previous studies have shown, the meaning constructed from the representation of the voltaic cell may not be scientifically acceptable which is concerning considering how ubiquitous this external representation is across chemistry textbooks.

## Chapter 1.4 Variation Theory as a Theoretical Framework

The goal of this study was to assess how students view the representation of the voltaic cell, specifically examining what features they attend to and the manner in which they do so. Because of this, variation theory was utilized as the theoretical framework which guided the design of this study. Variation theory, a derivation of phenomenography, aims to explain the variations in both students' experiences and their resultant unique understandings of the same learning event (Orgill, 2012). This variation in students' interpretations of a learning event is dependent on the limited amount of features that students can attend to at a given time (Marton & Booth, 1997). While a representation may have a gamut of features, there exists certain critical features: details that heavily influence one line of understanding from another (Marton & Tsui, 2004). As shown in a recent study, representations become most conducive for effective understanding when students discern the critical features (Bussey & Orgill, 2015). Critical features (such as the ionic interactions of the salt bridge or accretion on the cathode for the voltaic cell) are essentially components which anchor a student to facilitate further understanding of the learning event. If students fail to notice these critical features, they may interpret the representation in an unintended manner. As a result, instructors should cue students to notice and understand the critical features of a representation to anchor them in a shared and scientifically correct understanding.

Furthermore, variation theory is centralized around a term that is known as the *object of learning* which is defined throughout this thesis as the target concept for students to understand. For example, a given object of learning about acid base chemistry can be the electrochemistry of the voltaic cell. The object of learning is described in three forms: the intended object of learning, the enacted object of learning, and the lived object of learning (Scheme 6).



**Scheme 6:** Adaptation of Objects of Learning in Variation Theory (Bussey *et al.*, 2013)

The teacher sphere is a space that could represent an individual with the intention of facilitating student learning in a typical classroom setting. Within this space contains the intended object of learning which is what the instructor wants his or her students to learn about a particular concept. The student sphere on the other hand represents any individual entering the learning event who will experience the object of learning and develop a new or altered conception of that object. How the student interprets the object of learning is known as the lived object of learning which is essentially what is actually learned by the end of the day. In addition, the lived object of learning is also influenced by prior knowledge evinced by constructivism. From common experience, what one intends students to learn may not necessarily align with what they realistically learn after instruction. As the teacher sphere and the student sphere come together, the overlap is known as the space of learning (i.e. a classroom) which contains the enacted object of learning. The enacted object of learning is defined as what is possible for students to learn; in other words, what the instructor intends for the student to learn which can be limited due to a variety of factors present in the learning environment such as a lack of proper explanation, lack of clarity with the representation itself, etc. It is within this space where learning is co-constructed between the interactions of teacher and student and where teachers within this space must prioritize the act of students discerning critical features (Bussey, Orgill, & Crippen 2013). As shown in Scheme 2, all three objects interact with one another and are necessary to further ascertain why students can experience the same learning event in different manners.

In terms of application, variation theory can be a powerful framework in which to examine student understanding. For example, a study on molecular visualizations was conducted where learners, when exposed to variance in visualization features, were assessed on how variation would affect mental and visualization models by examining what students were attending to. The study had shown that while students demonstrated imperfect understandings, they nevertheless entered a transitional stage in which new, variant ideas began to mesh with pre-existing conceptions, thereby indicating progress towards a more scientific accurate mental model. The same study concluded that learners were more influenced by the very general characteristics and attended less to the more detailed features (Kelly, 2014). Another example is how variation theory was incorporated to investigate how students were utilizing and interpreting external representations in biochemistry, specifically the Shine-Dalgarno sequence (Bussey & Orgill, 2015). This study has shown external representations were indeed helpful for facilitating student learning; however, features that undergo variation (zooming, labeling, etc.) may cue students attention despite having little relevance to the portrayed event. As shown from these studies, variation theory is indeed an effective means of understanding why students experience a learning event in a gamut of ways. Variation theory was, therefore, selected as an appropriate theoretical framework for this project as it coincides with the methodological approach described below.

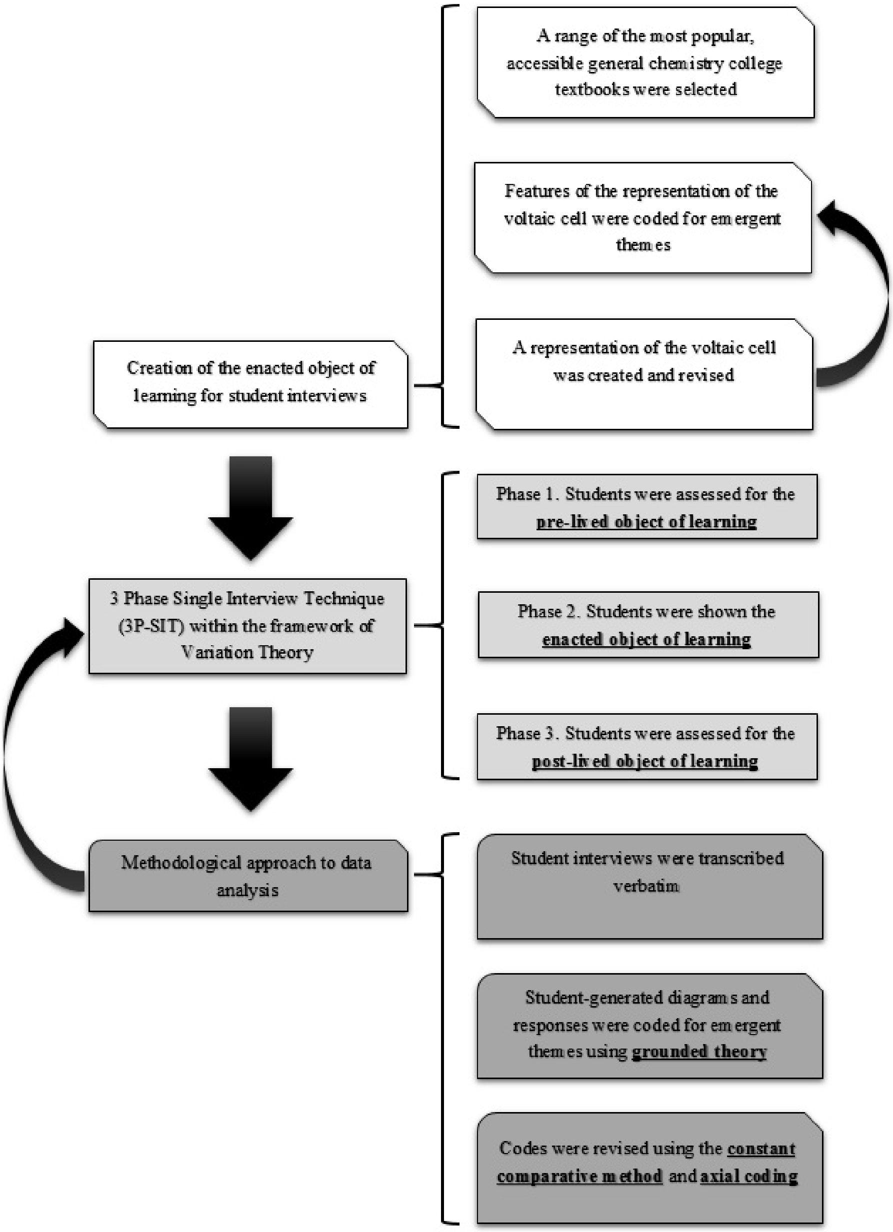
# Chapter 2 Methodology

In light of prior research highlighting both the positives and negatives effects of visual representations within science education, the purpose of this study was to assess third quarter general chemistry students and their understanding of submicroscopic features found within the representation of the voltaic cell through the lens of variation theory. The direction of this study is guided by the following research questions:

1. *What are common features of a voltaic cell external representation?*
2. *How do students understand the representation of the voltaic cell at the beginning of the interview in Phase One?*
3. *How do students view the representation of the voltaic cell in Phase Two?*
4. *Does viewing an external representation affect students' models of the voltaic cell in Phase Three?*
5. *Can students transition to the submicroscopic level of representation when orally cued to think at that level?*

These questions are significant because currently in the literature, there are few studies that delve into student perception and interpretation of the voltaic cell representation through a combination of interviews, student-produced drawings, and eye tracking data. Furthermore, because of the difficulty shown in transitioning between different levels of representation, I wanted to examine whether third quarter general chemistry students were able to accurately communicate the voltaic cell chemistry at the particulate level. While the representation of the voltaic cell is largely macroscopic and symbolic, there nevertheless is a plethora of submicroscopic information that from personal experience, students often neglect or misunderstand.

Ultimately, it is the submicroscopic level that students should be incorporating in their mental models because it is at this level where the fundamentals of chemistry really take place. The overall study is broken up into subsections and summarized in the flow chart below (Scheme 7).



**Scheme 7:** Flow Chart of Methodology

## Chapter 2.1 Design of Enacted Object of Learning

The representation of the voltaic cell shown to students (the enacted object of learning) was created as a result of an examination of six general chemistry college textbooks (Figure 1).

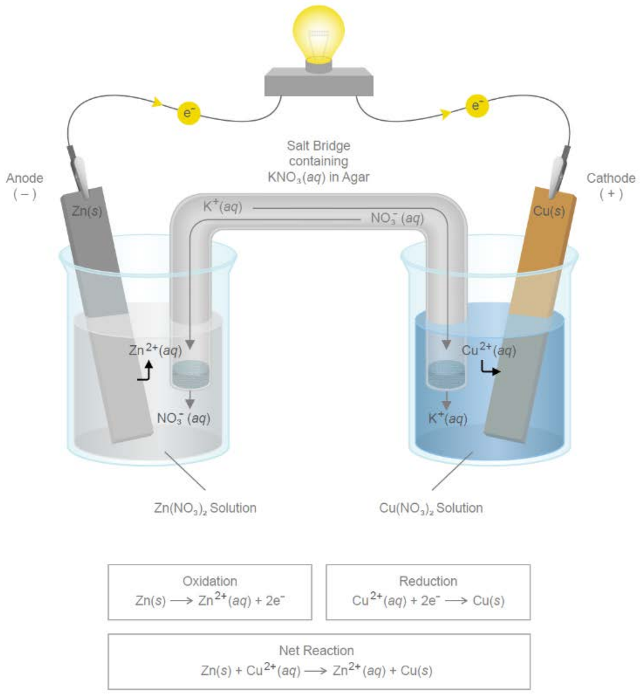
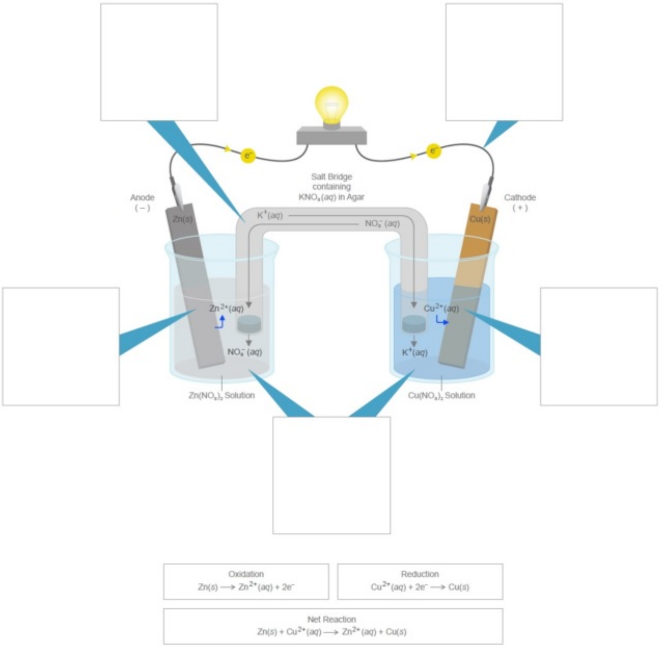


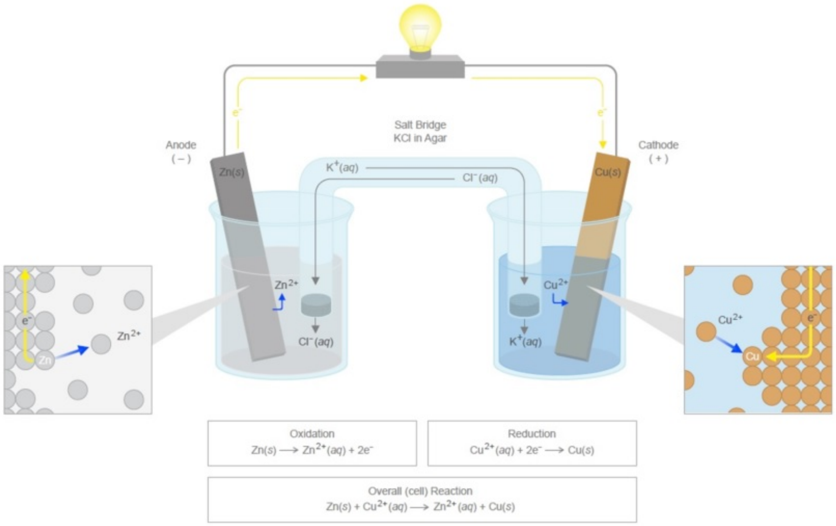
**Figure 1:** A Composite External Representation of the Voltaic Cell

I selected the following chemistry textbooks: *General Chemistry, 4th Edition* (McQuarrie, Rock, & Gallogly, 2011), *Chemistry the Molecular Nature of Matter and Change 4th Edition* (Silberberg, 2004), *Principles of Modern Chemistry 6th Edition* (Oxtoby, 2011), *Chemistry a Molecular Approach, 3rd Edition* (Tro, 2013), *Chemistry the Central Science 13th Edition* (Brown *et al.*, 2014), and *Chemistry 10th Edition* (Chang, 2010). McQuarrie's textbook was specifically chosen because this was the designated textbook utilized for third quarter general chemistry courses. The rest of the textbooks were chosen because they were the top-selling or most accessible textbooks to obtain by students via the internet. If one were to visit popular websites such as Amazon for the intention of purchasing textbooks, this selection is found at the beginning of the search results, are the highest rated, and were thus chosen for this study. Prior research has shown that choosing textbooks most available to students can serve as a convenient sample (Cohen, Manion, & Morrison, 2011). The rationale for choosing textbooks as guidelines to create this study's voltaic cell representation is that textbooks throughout many instances have shown their ubiquity in science education. Whether it is instructors who are dependent on textbooks as essential sources of information (King, 2001; Good, 1993; Wandershee, Mintzes, & Noval, 1994) or instructors who use textbooks as the structural guidelines to format a lesson plan (Mullis *et al.*, 2012), textbooks have an undeniable existence for chemistry students. Because prior textbook analysis research utilizing collegiate level chemistry had also used five or seven textbooks as their samples (Nyachwaya & Gillaspie, 2015; Bonicamp & Clark, 2007), it was important that at least six textbooks were selected to help create the composite voltaic cell representation. An additional reason for choosing six textbooks rather than just one is that multiple studies had shown that instructors have been dissatisfied with textbooks due to errors, lack of clarity resulting in alternative conceptions, and an inundation of data without the proper tools for student processing (Morris, Masnick, Baker, & Junglen, 2015; King, 2015; Bonicamp & Clark, 2007). Therefore, it was prudent to generate an external representation of the voltaic cell from the diagrams of the six selected textbooks in order to create an image that contains only the most commonly represented features of a voltaic cell representation that are most frequently exposed to students.

In the initial process of the textbook analysis, I scanned each of the voltaic cell representation found in the six textbook and inspected for similarities and differences with one another.  I analyzed every representation of the voltaic cell by generating emergent codes via grounded theory where the codes were revised upon iteration using the constant comparative method (Bernard & Ryan, 2010).  Examples of codes include the positioning of the electrodes, the color of the electrodes, and the presence of ions explicitly shown in solution (see Chapter 3, Table 1).  Once I had identified and coded for all the features of the voltaic cell from every textbook, I hired a graphics art designer who collaborated the features which had the most overlap among all the examined textbooks into a singular voltaic cell representation.  Considerations such as the color of solutions, appearance of the beaker, and the portrayal of the electron were revised upon subsequent reviews between myself and the faculty advisor.  The graphic designer and I created multiple versions of the voltaic cell, one of which included the submicroscopic level of representation which provided a standard to which we wanted the students to match in terms of their portrayal of the particulate chemistry found within the voltaic cell.

**Figure 2:** Prior Versions of the Enacted Object of Learning


Anode
( – )
Zn(s)
$e^-$
$e^-$
Salt Bridge containing $KNO_3(aq)$ in Agar
Cathode
( + )
Cu(s)
$K^+(aq)$
$NO_3^-(aq)$
$Zn^{2+}(aq)$
$NO_3^-(aq)$
$Cu^{2+}(aq)$
$K^+(aq)$
$Zn(NO_3)_2$ Solution
$Cu(NO_3)_2$ Solution
Oxidation
$Zn(s) \longrightarrow Zn^{2+}(aq) + 2e^-$
Reduction
$Cu^{2+}(aq) + 2e^- \longrightarrow Cu(s)$
Net Reaction
$Zn(s) + Cu^{2+}(aq) \longrightarrow Zn^{2+}(aq) + Cu(s)$


Salt Bridge
KCl in Agar
Anode
( – )
Cathode
( + )
$e^-$
$e^-$
Zn(s)
Cu(s)
$K^+(aq)$
$Cl^-(aq)$
$Zn^{2+}$
$Cl^-(aq)$
$Cu^{2+}$
$K^+(aq)$
$e^-$
Zn
$Zn^{2+}$
$Cu^{2+}$
Cu
$e^-$
Oxidation
$Zn(s) \longrightarrow Zn^{2+}(aq) + 2e^-$
Reduction
$Cu^{2+}(aq) + 2e^- \longrightarrow Cu(s)$
Overall (cell) Reaction
$Zn(s) + Cu^{2+}(aq) \longrightarrow Zn^{2+}(aq) + Cu(s)$

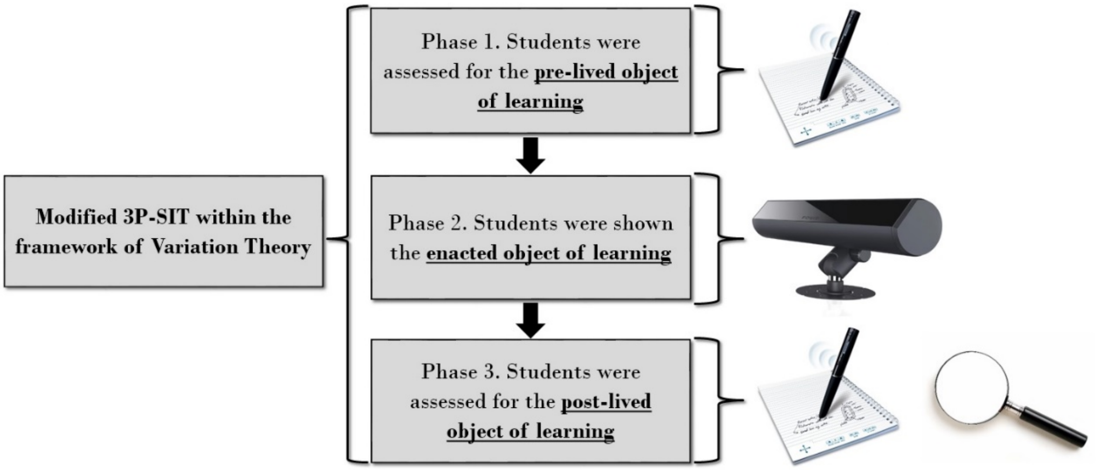
## Chapter 2.2 Population

All participants were undergraduate student volunteers enrolled in third quarter general chemistry at a large Southern Californian university in the spring, summer, and fall of 2015 in which a span of five classes taught by three unique professors were targeted. There was a total of 12 interviewed students, six of whom were male and six of whom were female. With the permission of the instructor, students were recruited via a speech presented at the beginning of the class. Solicitation speeches were delivered at approximately the same time that the instruction on the voltaic cell would begin in each respective class to ensure that students who participated would have similar degrees of prior knowledge in electrochemistry. Students volunteered by providing their email address and dates for interviews would be determined subsequently. The third quarter general chemistry course was selected because electrochemistry was part of the curriculum, thereby providing students with an initial knowledge of the voltaic cell. All of the courses which students were recruited from were listed as the same course in the college registrar (although taught by different professors), thus reinforcing the assumption that all the students who had participated received the same level of instruction relative to one another. Interviews were scheduled shortly after the solicitation speech was given, typically one to two weeks afterwards as stated by students during the interview. This study was only limited to students who were concurrently enrolled in the third quarter general chemistry course; students who had taken the course in previous quarters were not eligible for this study. The reason is that I wanted to conduct the interviews with the student when information on the voltaic cell representation was most recently introduced via instruction.

## Chapter 2.3 Three Phase Single Interview Technique

A total of twelve students were interviewed for approximately 45-60 minutes in semi-structured, individual, and private interviews to assess their understanding of the representation of the voltaic cell using a modified version of the Three-Phase Single Interview Technique (3P-SIT) with variation theory as the theoretical framework (Schönborn, Anderson, & Mnguni, 2007). The 3P-SIT is a semi-structured interview technique that is used as a neutral and flexible clinical instrument. By design, 3P-SIT allows the student to speak freely while enabling the modification of pre-determined questions in order to adapt to emergent student response patterns during the interview. (Schönborn & Anderson, 2009). This allows interviewers to probe more deeply into student understanding (Bretz, 2007). The 3P-SIT model was chosen because it enables the researcher to probe student prior knowledge, assess how students interpret the presented external representations, and whether the learning event instigates change in the students' illustrations. Each interview conducted consisted of three phases: (1) investigating students' prior knowledge of voltaic cells prior before any external representation exposure; (2) determining students' interpretations and reasoning of a common voltaic cell external representation; and (3) assessing if there were any influential effects the representation may have on student understanding. For this study, I conducted the 3P-SIT using the framework of variation theory where the intended object of learning (what instructors intend for students to learn) was the particulate chemistry involved within the voltaic cell (Bussey, Orgill, & Crippen, 2013).

Furthermore, the 3P-SIT was modified to encapsulate the pre-lived object of learning, the enacted object of learning, and the post-lived object of learning in its design (Scheme 8).



**Scheme 8**. Flow Chart of 3P-SIT

Phase One consisted of examining student's pre-lived object of learning which is what a student already knew before the learning event took place (Bussey *et al.*, 2013). In other words, Phase One is very similar to a pre-test that measures the amount of prior knowledge students demonstrate with respect to the representation of the voltaic cell as well as related electrochemistry upon entering the interview. During this phase, students would use a digital pen to articulate or draw their understanding of the voltaic cell, its features, and chemical processes. Taking approximately a total of 20 minutes, the interviewer would initialize Phase One by first prompting the student with a predetermined introduction (see Student Interview Guide in Supplemental

Files). All 12 interviews began with my paraphrasing an introductory excerpt from the Student Interview Guide that describes instructions that students will follow for the remaining duration. After being prompted, students recalled all of the salient features of the voltaic cell and I would wait so as to allow student responses to naturally occur. Once the student begins drawing the voltaic cell, the interviewer would probe student understanding using pre-determined questions alongside with questions specific to the ideas that the student were providing during that interview. As a result, the interview became more reminiscent of a controlled conversation that allowed the interviewer to critically analyze the rationale students were employing to justify both their illustrations and their scientific conceptions. However, as the interviewer, I would still refrain from any potential chance of leading or biasing the student to respond in a certain manner (Schönborn & Anderson, 2009). Specifically, I would avoid mentioning any particular terminology or its significance with the voltaic cell (i.e. anode, accretion, and spontaneity) if students did not state and explain those terms first. In addition, if I had mentioned certain features of the voltaic cell, this may influence students to feel that whatever was mentioned would be more important for further discussion, thereby affecting the priority with which they assign to particular features during the interview. I wanted the interviewed student to convey information that was derived as much from his or her prior knowledge as possible without any additional input from myself.

Phase Two involved introducing students to an external representation of the voltaic cell that served as the enacted object of learning (i.e. what I intend for students to take away from the representation of the voltaic cell). In other words, the same representation of the voltaic cell (Figure 1) was shown to all 12 participants. Although the enacted object of learning is often regarded as a classroom environment (Marton & Tsui, 2004), any instructional tool such as a textbook diagram or online learning materials can potentially serve as the enacted object of learning (Bussey *et al,*. 2013). The second phase was designed to allow the student to confront their knowledge of the underlying chemistry within the voltaic cell external representation. Not only did students have to extract information from features that they may not have included before but also they had extract meaning from those aforementioned features as well (Kindfield, 1993). The enacted object of learning in this case is a representation of the voltaic cell that only exhibits the macroscopic and symbolic levels of representation. It was by design that the submicroscopic level was omitted. For example, the accretion on the cathode, the disintegration on the anode, and the ionic interactions within the solution were all absent from the enacted object of learning. Students were given approximately 5-10 minutes to examine and interpret the external representation in order to make sense of the information provided. During this process, I would ask that the student to think out loud as the student examined the provided external representation and compared the differences with his or her previously drawing. Students were not told if their descriptions was right or wrong but were rather instructed to elaborate or clarify their statements. Three case studies were conducted that utilized an eye tracker during phase two, where a device would measure both the student's gaze path and fixation time with regards to the enacted object of learning.

Phase Three asked students to create their post-lived object of learning (i.e., how they portray the voltaic cell after seeing a pre-designed version) via re-illustrating and describing a new drawing of the voltaic cell or annotating their previous ones. During this event, I would spend approximately 30 minutes identifying the types of effects (e.g., the inclusion or exclusion of conventions, labels, and shapes) the external representation may have had on the student's conception of the voltaic cell and if the external representation itself had an effect on its own interpretation (Schönborn & Anderson, 2009). Just as before, I would probe the student's understanding and justification of whatever features of the voltaic cell are portrayed in order to assess their scientific accuracy. Throughout this portion of the interview, it was an effective time to compare the pre- and post-lived object of learning and evaluate the extent of the external representation's influence. By delving deeper, I as the interviewer could elucidate reasons that explained why alternative conceptions persisted or whether concepts of the voltaic cell remained unclear for student interpretation. Furthermore, a fourth phase was included as an addendum to the third phase in which students were asked to pretend that they had a magnifying glass shown towards the end of the student interview guide (See Student Interview Guide in Supplemental Files). This prompt was presented throughout all twelve interviews right as the third phase concluded. The reason for including this is to assess if students were capable of transitioning from macroscopic and symbolic to submicroscopic by illustrating the particulate level of chemistry found throughout the voltaic cell. Once this portion of the interview had been completed, the interview was effectively over. All interviews were audio recorded under permission using IRB-approved consent forms and were later transcribed verbatim. Each student was given a pseudonym to maintain anonymity.

## Chapter 2.4 Digital Pen

During the interview, a digital pen and dot paper were utilized for two purposes: recording the audio portion of the interview and syncing the audio with what students were drawing in real time as well. The Echo™ smart pen by Livescribe is an all-in-one device that serves as a computer, infrared camera, microphone, and pen (Figure 3).

**Figure 3:** Echo Smart Pen

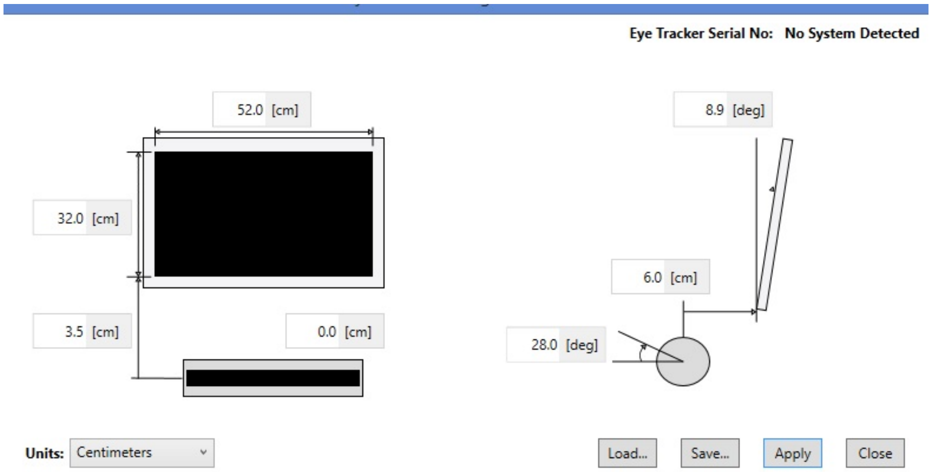
In combination with the Livescribe dot paper, one can utilize the tool bar to access the record, pause, and stop buttons at his or her convenience. Once a user has finished recording a session, the file can be transferred onto either a Windows or Mac computer using the Livescribe user interface. Each session has a playback feature in which one can not only listen to the recorded audio but also see the drawings of the pen appear in real time as well. The Echo™ smart pen comes in a 2 GB or 8 GB version where each gigabyte offers approximately over 100 hours of audio (Livescribe, 2007).

As shown by prior research, there are many advantages of using a digital pen. For example, employing a digital pen enables researchers to digitally revisit student drawings that have already been synced with their respective audio recordings which is extremely valuable during the analysis process (Linenberger & Bretz, 2012). In addition, a digital pen is still similar enough to a regular pen insofar that it eludes the intimidation or confusion that may come from more advanced technological innovations. Prior research has shown that pen and paper have been preferred over more technologically complicated devices in students, soldiers, and physicians (Oviatt, 2006; Cohen & McGee, 2004; Gorman *et al.*, 2000). As a result, experiencing cognitive load due to overly-complicated interfaces is a legitimate concern which is addressed by the simplicity and familiarity of a digital pen. Individuals sometimes when transitioning to new technology may have sacrificed some degree of ability and time in exchange. To ensure that this interview was conducted with as a few barriers as possible, a digital pen was utilized as an effective compromise.

In this study, the recordings of both the audios and the students' drawings were used as foundations for data analysis. Firstly, students would use the digital pen for illustrative purposes throughout the interview, specifically at Phases 1 and 3. Students would use the digital pen and provide their illustrations on the dot paper provided. With regards to the audio recording, the digital pen remained on for the entirety of the interview and was placed near the student at all times to ensure that the student's voice could be clearly picked up. After the interview, audio recordings from the digital pen was utilized to transcribe what the students had said verbatim. Oftentimes, simultaneous playback of audio and the student’s drawing was necessary in order to clarify certain elements that students may have neglected to specify orally in terms of their drawings. For example, vague words such as “this” found throughout the student’s commentary was better contextualized when coordinated with what the student had drawn at that moment of time. The recordings of student drawings were utilized for comparison and assessment purposes with regards to students’ Pre-Lived and post-lived objects. Because their illustrations could be paused and captured at certain moments of time, I could generate pre- and post-lived objects even if students decided to annotate over their initial drawing instead of producing an entirely new one. Once I had the pre- and post-lived objects that students had produced, I then analyzed what types of features were included initially, whether or not the features incorporated was correctly done, what features were initially omitted, whether there was any change in terms of features incorporated afterwards, if the Post-Lived features were correctly done, and if there were Post-Lived features that remained omitted.

## Chapter 2.5 Eye Tracker

A FOVIO seeing machine with EyeWorks Software Suite was used to collect data on how students viewed the enacted object of learning. The display monitor used in conjunction with the eye tracker was a 24-in monitor with a resolution of 1920 x 1080 pixels and a refresh rate of 59 Hz. The eye tracker itself is a non-intrusive device: students would just view the monitor (placed approximately 25 in away from the student) as the eye tracker would track and record how students viewed the displayed image. The angle of pitch (from the floor) was set to 28.0 deg, the z offset (how far the display is behind the eye tracker) was set to 2.4 in, and the angle of pitch of the screen (from vertical) was set to 8.9 deg (Figure 4).



Eye Tracker Serial No: No System Detected

Units: Centimeters

**Figure 4:** Eye Tracker Settings

The eye tracker's sampling rate was set to 60 Hz. In addition, the eye tracker was kept at default settings for a duration of 0.075 seconds at a threshold of 5 pixels when generating heat maps. Furthermore, fixations were utilized for constructing heat maps. The eye tracker and monitor were utilized by a 3.50 GHz Intel Xeon E5 v3 desktop computer equipped with Windows 8.1, a 2047MB NVIDIA Quadro K620 graphics processing unit, and 16 GB RAM at 1064 MHz.

Case studies were conducted for three participants that utilized the eye tracker during Phase Two of the interview. The eye tracker provided two sources of data: the gaze path and the fixation heat map. The purpose of the gaze path was to visualize how students viewed the enacted object of learning. This was determined by tracking the convergence of both left and right pupils as a singular point as this point navigated through the enacted object of learning. The purpose of the fixation heat map was to visualize how much time students attended to particular features relative to the whole enacted object of learning. By monitoring the convergence of students pupils, the eye tracker would generate fixation data that would attribute warmer colors (such as red) to regions to which students spent more time fixating and cooler colors (such as blue) to regions to which students spent less time fixating.

With the gaze path, I was able to monitor how students oriented themselves when viewing the enacted object of learning. By setting the time interval window, one could examine how students navigated through the enacted object of learning within the first few seconds or for the entirety of the interview. Dots would be generated and portioned by different colors to indicate different time intervals. During the preliminary analysis, multiple intervals (10 seconds, 30 seconds, and 60 seconds) of the gaze path were attempted and it was found that time intervals exceeding 10 seconds would clutter the figure with excessive data points. In addition, because the literature did not state a consensus on a standardized time interval for gaze paths, the selection of 10 seconds for this study was deemed to not be erroneous. As a result, the initial ten seconds when students were exposed to the enacted object of learning was arbitrarily chosen as the designated length of time for gaze path data.

In addition, the fixation data provided by the eye tracker was utilized to generate heat maps of what students attended to. By creating specific regions or areas of interest, the eye tracker can monitor the duration of an individual's eyes remaining within the boundaries of a particular area of interest. For Phase Two of this study, five areas of interest were identified: Anode, Cathode, Salt Bridge, Reactions, and Light bulb & Wire (Figure 5). The reason that these categories are different from the initial categories of the enacted object's features is that when generating areas of interest, one must avoid as much overlap as possible.  The voltaic cell representation inherently contained a lot of overlap so new areas of interest were generated towards the end of the study specifically for the eye tracker.

Once the data was compiled, the eye tracker‘s software could generate percentages in terms of how much time one attended to a particular area of interest with respect to total time in the form of heat maps.  The time window for the fixation heat map was set to the full duration of Phase Two for these three students. Combining both the gaze path and the fixation data, I intend to use the eye tracker as a means of further elucidating how students are viewing the representation of the voltaic cell, whether this was influenced by their pre-lived object, and whether their viewing of the enacted object of learning influenced student drawings of their post-lived object.

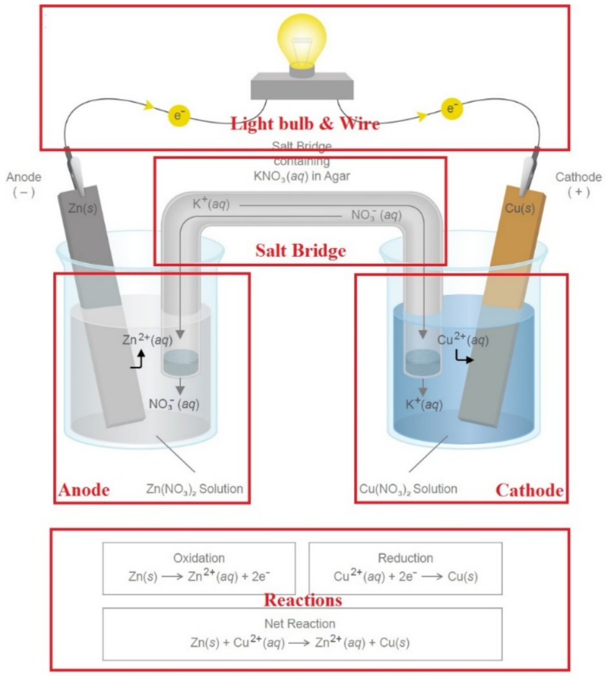


**Figure 5:** Areas of Interest for Eye Tracker

## Chapter 2.6 Data Analysis

I coded student responses for emergent themes using a grounded theory approach. Grounded theory is a methodological strategy that relies on the inductive reasoning in the study of social phenomena (Glaser & Strauss, 1967). Inductive research involves searching for patterns within the observations and developing explanations for said patterns. This grounded theory approach is a very powerful qualitative tool in the sense that it facilitates a theory to emerge from the data, thereby linking the two such that the theory can very accurately relate to the phenomenon within one's study (Kunkwenzu & Reddy, 2008). In addition, grounded theory has a very widespread presence outside of science education as well. From investigating victims of school bullying to exploring the experiences of disability among Taiwanese adults, fields that touch upon cultural and social anthropology also utilize grounded theory to make claims about their populations of study (Lin, Knox, & Barr, 2014; Thornberg, Halldin, Bolmsjö, & Petersson, 2013). I then revised categorized themes using the constant comparative method where I would recursively compare incoming, new data with older data. After categorizing, coding, and connecting emergent themes, I would periodically adjust any previously established codes to allow the comparative method to progress (Lincoln and Guba, 1985; Bernard & Ryan, 2010). For example, certain features that students would describe were later modified by partitioning into more specific categories to encompass the answers of subsequent students such as having one category referring to the anode being represented as a metal bar to having two categories referring to the anode being represented as a rectangle and the anode being described with a specific composition. As a result, the theory is continually modified until one reaches theoretical saturation meaning that the no new data emerges from continued analysis and that the concepts have become well developed (Bernard & Ryan, 2010). With regards to data collapsing, I also implemented axial coding within the data analysis. Axial coding is the process of identifying a frame of relationship to relate codes with one another via both inductive and deductive reasoning (Strauss & Corbin, 1990; Strauss & Corbin, 1998). For this study, features that students would exhibit in their diagrams later became broader designations of the voltaic cell such as the anode, cathode, salt bridge, etc.

Because of the prevalence of coding used throughout this study, it was important to have effective intercoder reliability to ensure that all the coders are consistently seeing the same trends given a sample text (Bernard & Ryan, 2010). Codes were validated by an external coder where inconsistencies were revised via subsequent meetings until there was mutual agreement in terms of the data analysis. Over the course of five reconciliation periods, the external coder and I convened and cross-checked the types of features students had included in their pre- and post-lived objects of learning. Within the initial meetings, discrepancies between myself and the external coder in terms of what we observed were reduced once codes were revised and specified. By the end of our meetings, there was mutual agreement between what the external coder and I had observed with regards to features students included in their drawings.

Student interviews, once transcribed, were assessed in a pre-post format. I tracked students' conceptual understanding of the voltaic cell that consisted of scientifically accurate and potential alternative conceptions in their prior knowledge and if said conceptions persisted or changed after the learning event. I applied codes for student-generated diagrams of the voltaic cell to validate if a student had illustrated a correct conception both before and after, if a student had failed to illustrate a feature before and after, if a student had failed to illustrate a feature before but included it correctly after, and if a student had correctly included a feature before but failed to illustrate it correctly afterwards. Codes were further revised upon newly incorporated features that students would potentially provide in their drawings (such as the instances of submicroscopic representation). In addition, I analyzed the Pre-Lived and post-lived objects of learning that students had generated by means of comparison to assess differences or similarities in included macroscopic, symbolic, and submicroscopic features. Eye tracking data, if available, was also utilized to create another perspective to interpret students' pre- and post-lived objects of learning.

# Chapter 3 Results and Discussion

This project began with a textbook analysis in order to determine which features were commonly available to students. These features were used to create a composite representation, the rationale being that I wanted to show students a representation of the voltaic cell that had the most similar appearance to other voltaic cell external representations found across different textbooks. During the initial textbook analysis, I identified 31 features of the voltaic cell to attribute meaning to (Table 1). Features were determined by listing out all of the different visual details that a voltaic cell representation possessed. For example, I considered a variety of factors such as positioning, usage of symbolism, color, presence, composition, and purpose. Table 1 was constructed to be color-coordinated where each textbook was attributed a certain color. If the textbook's representation of the voltaic cell contained the feature in question, the corresponding cell would be shaded the color of that respective textbook. If a cell were left blank, this indicated that the representation of the voltaic cell of that particular text book did not possess the aforementioned feature. It was found that 23 of these features were commonly exhibited by a majority of the external representations found in the textbook (where a majority was defined as four or more textbooks). In terms of the shared features, the most common type were the macroscopic levels such as the designation of electrodes as metals. The more uncommon types of features that exhibited less overlap among textbooks (where three or less textbooks shared commonality) were symbolic and primarily dealt with ionic or electronic movement. Other than the processes of accretion and degradation, features of the submicroscopic level were largely absent.

**Table 1:** Textbook Analysis
Observed Common Features among Textbooks Most Available to Undergraduate Students

| Features | General Chemistry,4th Edition | Chemistry The Molecular Nature of Matter and Change, 4th Edition | Principles of Modern Chemistry, 6th Edition | Chemistry A Molecular Approach, 3rd Edition | Chemistry The Central Science, 13th Edition | Chemistry, 10th Edition |
|---|---|---|---|---|---|---|
| Left electrode is designated as anode |  | ■ |  | ■ | ■ | ■ |
| Left electrode is marked negative | ■ | ■ |  | ■ | ■ |  |
| Left electrode is made of zinc | ■ | ■ |  | ■ | ■ | ■ |
| Left electrode is silver | ■ | ■ |  | ■ | ■ | ■ |
| Left electrode solution is | ■ | ■ |  | ■ | ■ |  |
| Right electrode is designated as |  | ■ |  | ■ | ■ | ■ |
| Right electrode is marked as | ■ | ■ |  | ■ | ■ |  |
| Right electrode is made of | ■ | ■ |  | ■ | ■ | ■ |
| Right electrode is copper | ■ | ■ |  | ■ | ■ | ■ |
| Right electrode |  | ■ | ■ |  | ■ | ■ |
| Voltmeter is placed between the | ■ | ■ | ■ |  | ■ |  |
| Salt bridge is placed between two | ■ | ■ | ■ | ■ | ■ | ■ |
| There are porous plugs on each end of the salt bridge |  |  | ■ | ■ |  | ■ |

**Table 1:** Textbook Analysis, Continued
Observed Common Features among Textbooks Most Available to Undergraduate Students

| Features | General Chemistry,4th Edition | Chemistry The Molecular Nature of Matter and Change, 4th Edition | Principles of Modern Chemistry, 6th Edition | Chemistry A Molecular Approach, 3rd Edition | Chemistry The Central Science, 13th Edition | Chemistry, 10th Edition |
|---|---|---|---|---|---|---|
| Zinc ion moves from left electrode into left electrode solution | ▨ | ▨ |  | ▨ | ▨ | ▨ |
| There is a zoomed in depiction of oxidation on the particulate level |  | ▨ |  | ▨ | ▨ | ▨ |
| Salt bridge anion moves from salt bridge to left electrode solution | ▨ |  |  |  |  |  |
| The process of consumption is shown via oxidation |  | ▨ |  |  |  | ▨ |
| Correct number of electrons that move out of the anode and through the wire is shown |  | ▨ |  | ▨ | ▨ | ▨ |
| Copper ion moves from right electrode solution into right electrode | ▨ | ▨ |  | ▨ | ▨ | ▨ |
| There is a zoomed in depicion of reduction on the particulate level |  | ▨ |  | ▨ | ▨ | ▨ |
| Salt bridge cation moves from salt bridge to right electrode solution | ▨ |  |  |  |  |  |
| The process of accretion is shown via reduction |  | ▨ |  | ▨ | ▨ | ▨ |

**Table 1:** Textbook Analysis, Continued
Observed Common Features among Textbooks Most Available to Undergraduate Students

| Features | General Chemistry,4th Edition | Chemistry The Molecular Nature of Matter and Change, 4th Edition | Principles of Modern Chemistry, 6th Edition | Chemistry A Molecular Approach, 3rd Edition | Chemistry The Central Science, 13th Edition | Chemistry, 10th Edition |
|---|---|---|---|---|---|---|
| Correct number of electrons that move through the wire and into the cathode is shown |  | ■ |  | ■ | ■ | ■ |
| Electrons are shown moving from the anode, through the wire, and to the cathode | ■ | ■ |  | ■ | ■ | ■ |
| Ions are moving within the salt bridge | ■ | ■ | ■ | ■ | ■ | ■ |
| The chemical equation for oxidation is provided |  | ■ |  | ■ | ■ | ■ |
| It is shown what the left electrode solution consists of | ■ |  |  | ■ |  | ■ |
| The chemical equation for reduction is provided |  | ■ |  | ■ | ■ | ■ |
| It is shown what the right electrode solution consists of | ■ |  |  | ■ |  | ■ |
| The net redox equation is provided |  | ■ |  |  |  | ■ |
| It is indicated what the salt bridge is comprised of | ■ |  |  | ■ |  |  |

Of the 31 features identified, they were later modified to specifically incorporate strictly macroscopic and symbolic designations. As a result of the constant comparative method, the need to generate further codes based off of what students had produced that the initial textbook analysis did not account for, and the required specificity for distinguishing between macroscopic and symbolic levels of representation, I later created 52 codes utilized throughout the composite voltaic cell figure that were shown to students (Table 2). One of the first processes involved in the generation of new codes was due to the necessity to distinguish what a student represented and what was being assumed later in the analysis. For example, a student could represent a rectangle for the anode but may not explicitly state or represent the conception that the anode were comprised of a metal. Thus, separate codes were needed to have been utilized to avoid assuming whether students conveyed or described a certain conception. In addition, features were assigned either a macroscopic or symbolic designation. If the feature were a physical aspect of the voltaic cell that could be experientially observed or felt, this particular feature would be given a macroscopic designation. If a feature employed the usage of a conventional phrasing or certain letters to signify a chemical meaning or identification (such as the abbreviated titles of elements found on a periodic table), these would be given symbolic designations. Arrows designating direction would also be classified as an instance of symbolic representation. In terms of the new codes that emerged from subsequent reviewing of new data, many of these codes originated from student frequently providing partial representation of a particular code. For example, student may represent an ion in its abbreviated symbolic form but fail to incorporate the symbolic designation for its phase; and thus, in order to avoid assuming what the student may or may not describe, multiple codes were necessary to distinguish what features students were representing. Finally, in order to avoid visually cueing students to think at a submicroscopic level during the interview, any submicroscopic representational feature was purposefully omitted from the composite voltaic cell figure. The purpose of this study was to examine whether students were capable of transitioning to the submicroscopic level in terms of their representation when just shown the macroscopic and symbolic levels of representation. I wanted to avoid cueing students visually by removing submicroscopic features from the enacted object of learning because I did not want to influence student understanding and potentially the manner in which students would represent their post-lived object. If students were shown submicroscopic levels of representation and incorporated afterwards in their post-lived objects, it would be difficult to attribute this ability to convey the submicroscopic level to student prior knowledge or external influence.

The coded features utilized in the composite image of the voltaic cell were later organized into to five broad categories: the anode, the cathode, the salt bridge, the wire and light bulb, and miscellaneous. The anode category was broadly defined as everything present on the left hand side, such as the anode itself, the solution identity, and the ions found within the solution. The cathode category was defined as everything present the right hand side, similarly incorporating its respective features in a similar manner as that of the anode category. The salt bridge category was defined as the region incorporating the salt bridge, the salt bridge ions, and the symbolic usage of arrows to notify the direction of which the salt bridge ions would travel. The light bulb & wire category was defined as the topmost region of the voltaic cell representation, including features such as the directionality of electron flow, the presence of a wire, and a light bulb or voltmeter.  The last category, titled miscellaneous, was utilized as an encompassing theme for features that were generally present throughout the entire voltaic cell diagram that may not have belonged to a singular region.  Features belonging in this category had overlap with other regions and was thus difficult to attribute to one category over the other.  For example, the symbolic representation of electrons, the net reduction oxidation reaction, and the presence of solution or ions anywhere belonged to the miscellaneous category.

**Table 2:** Critical Features of the Enacted Object of Learning

| | |
|---|---|
| **Anode** | A rectangle is drawn in association with the anode (left side of diagram) [macro] |
| | The anode composition is defined as zinc [macro] |
| | The subscript (s) is used to describe the zinc as solid [symbolic] |
| | Anode is found on the left [macro] |
| | The zinc solution color is identified (gray) [macro] |
| | Over time, the anode will begin losing mass [macro] |
| | Aqueous solution of the anode is identified as Zn(NO3)2 [symbolic] |
| | Zinc ion is identified to be in the anode beaker [symbolic] |
| | Zinc ion has a 2+ charge in the superscript [symbolic] |
| | The subscript [aq] is used to describe the zinc ion [symbolic] |
| | Nitrate ion (from salt bridge) is identified to be in the anode beaker [symbolic] |
| | NO3 is used to label the nitrate [symbolic] |
| | The nitrate ion (from salt bridge) has a negative symbol in the superscript [symbolic] |
| | The subscript [aq] is used to describe the nitrate ion (from salt bridge) [symbolic] |
| | A negative sign is used to label the anode [symbolic] |
| | Zn is used to label zinc [symbolic] |
| | The anode ion goes from the anode into solution [symbolic] |
| | Oxidation occurs at the anode and the oxidation reaction is written [symbolic] |
| | Electrons come off of the anode [symbolic] |
| **Cathode** | A rectangle is drawn in association with the cathode (right side of the diagram) [macro] |
| | The cathode composition is defined as copper [macro] |
| | The subscript (s) is used to describe the copper as solid [symbolic] |
| | Cathode is found on the right [macro] |
| | The copper solution color is identified (blue) [macro] |
| | Over time, the cathode will begin accumulating mass [macro] |
| | Aqueous solution of the cathode is identified Cu(NO3)2 [symbolic] |
| | Copper ion is identified to be in the cathode beaker [symbolic] |
| | Copper ion has a 2+ charge in the superscript [symbolic] |
| | The subscript [aq] is used to describe the copper ion [symbolic] |
| | Potassium ion (from salt bridge) is identified to be in the cathode beaker [symbolic] |
| | K is used to label the potassium [symbolic] |
| | The potassium ion (from salt bridge) has a positive symbol in the superscript [symbolic] |
| | The subscript [aq] is used to describe the potassium ion (from salt bridge) [symbolic] |
| | A positive sign is used to label the cathode [symbolic] |
| | Cu is used to label copper [symbolic] |
| | The cathode ion goes from solution onto the cathode [symbolic] |
| | Reducton occurs at the cathode and the reduction reaction is written [symbolic] |
| | Electrons go into the cathode [symbolic] |
| **Salt Bridge** | Salt bridge is placed between the two beakers [macro] |
| | The salt bridge is identified as KNO3 [symbolic] |
| | The negative ion goes from the salt bridge into the anode beaker (NO3-) [symbolic] |
| | The positive ion goes from the salt bridge into the cathode beaker (K+) [symbolic] |
| | The salt bridge has ions [symbolic] |

**Table 2:** Critical Features of the Enacted Object of Learning, Continued

| | |
|---|---|
| Light Bulb and Wire | There is something connecting the anode and cathode (wire) [macro] |
| | There is a lightbulb or voltmeter in the middle of the wire [macro] |
| | The light bulb is lit to indicate a flow of electrons [macroscopic] |
| | Electrons flow from left to right [symbolic] |
| | Electrons flow through whatever is connecting the two half cells (wire) [symbolic] |
| Misc | Electrons are represented as e- [symbolic] |
| | The net reaction of the redox process is written out [symbolic] |
| | There are two containers representing the two half cells [macro] |
| | Liquid is found within the container [macro] |

## Chapter 3.1 Phase One: Evaluating Pre-Lived Object of Learning

Throughout this study, I defined the majority of the population to constitute as more than half of the interviewed participants. For the purpose of the following analysis, commonly represented features will be defined as what the majority incorporated in their drawings. Within the first phase of the interview, a majority was able to represent ten critical features of the voltaic cell figure (Table 3).

**Table 3:** Features that a Majority Included in Pre-Lived Object

| | |
|---|---|
| **Anode** | A rectangle is drawn in association with the anode [macro] |
| | Anode is found on the left [macro] |
| **Cathode** | A rectangle is drawn in association with the cathode [macro] |
| | Cathode is found on the right [macro] |
| | Cu is used to label copper [symbolic] |
| **Salt Bridge** | Salt bridge is placed between the two beakers [macro] |
| **Light Bulb and Wire** | There is something connecting the anode and cathode (wire) [macro] |
| **Misc.** | Electrons are represented as e- [symbolic] |
| | There are two containers representing the two half cells [macro] |
| | Liquid is found within the container [macro] |

Of these ten, eight were macroscopic features while two were symbolic features. Specifically, what students most commonly represented initially were the identification of an anode and cathode via rectangles, the anode and cathode's positioning relative to one another, two beakers containing liquid, a salt bridge, a wire, and the presence of electrons. From the student initial drawings, a majority of the students recalled and prioritized the macroscopic aspect of the voltaic cell the most. There could be several underlying reasons why students incorporated mostly macroscopic features in their initial drawings. There is the possibility that macroscopic features are more easily recognizable and recallable by students. Macroscopic features, in the context of the voltaic cell, refer to physical aspects such as beakers, metals, and solution. Students could potentially recall these more effectively due to prior instruction, experience with utilizing a voltaic cell as an experiment, etc. For example, Student AC had done a voltaic cell experiment during high school which may have instigated the recalling of the salt bridge.

> Student AC: Um...so in high school we built the voltaic cell...
>
> Interviewer: Mmhmm
>
> Student AC: And...when we had it without the salt bridge we had like a little light bulb at the top and without the salt bridge, there was no light. Like...it just didn't light up at all.

If students have a physical experience with respect to the voltaic cell that is outside of what is commonly provided in textbooks, it would be reasonable that students could more easily recall those macroscopic features as shown through Student AC. Another potential reason that may limit the student to just macroscopic features could be the difficulty that students may find with regards to symbolic and submicroscopic levels of representation.  With abundant topics dealing with specific chemical processes involving matters such as ion identification or the concept of solution neutralization, students might avoid using those levels of representation due to potential uncertainty with regards to those topics.  There also is the possibility that students were limited in their ability to draw or discuss matters pertaining to symbolic or submicroscopic features of the voltaic cell due to lack of familiarity with the topic in question.

In terms of what the minority of the population included in their initial drawings, these features were primarily of the symbolic level of representation.  Of the 42 features that were not included by the majority of the population, 35 of those were symbolic features (Table 4).  Specifically, many students tended to neglect identifying the phases of ions and metals found throughout the voltaic cell as well as the identification of specific ions and metals utilized in the reduction-oxidation reactions.  Another common symbolic feature that a majority of the population did not incorporate was the directionality of ionic and electronic movement in the voltaic cell.  There were few instances of macroscopic features that a majority of the population did not incorporate in their pre-lived object, the primary example being the colors of the solution.  Finally, there were no instances of submicroscopic features found within the pre-lived objects.  What these results had shown was that if students were asked to represent a voltaic cell diagram, a majority of the assessed population would provide a diagram consisting of mostly macroscopic elements while a majority would ignore many of the symbolic features involved.  Specifically, students did not include ionic interactions with the salt bridge and the solutions of anode and cathode.

In addition, none of the participants found it relevant in their initial diagrams to include submicroscopic elements.  This conveyed both the notions that macroscopic features of the voltaic cell may be more easily remembered as well as macroscopic features being more salient to students' models of the representation of the voltaic cell during this phase of the interview.

**Table 4:** Features that a Minority Included in Pre-Lived Object

| | |
|---|---|
| **Anode** | The anode composition is defined as zinc [macro] |
| | The subscript (s) is used to describe the zinc as solid [symbolic] |
| | The zinc solution color is identified (gray) [macro] |
| | Over time, the anode will begin losing mass [macro] |
| | Aqueous solution of the anode is identified as Zn(NO3)2 [symbolic] |
| | Zinc ion is identified to be in the anode beaker [symbolic] |
| | Zinc ion has a 2+ charge in the superscript [symbolic] |
| | The subscript [aq] is used to describe the zinc ion [symbolic] |
| | Nitrate ion (from salt bridge) is identified to be in the anode beaker [symbolic] |
| | NO3 is used to label the nitrate [symbolic] |
| | The nitrate ion (from salt bridge) has a negative symbol in the superscript [symbolic] |
| | The subscript [aq] is used to describe the nitrate ion (from salt bridge) [symbolic] |
| | A negative sign is used to label the anode [symbolic] |
| | Zn is used to label zinc [symbolic] |
| | The anode ion goes from the anode into solution [symbolic] |
| | Oxidation occurs at the anode and the oxidation reaction is written [symbolic] |
| | Electrons come off of the anode [symbolic] |
| **Cathode** | The cathode composition is defined as copper [macro] |
| | The subscript (s) is used to describe the copper as solid [symbolic] |
| | The copper solution color is identified (blue) [macro] |
| | Over time, the cathode will begin accumulating mass [macro] |
| | Aqueous solution of the cathode is identified Cu(NO3)2 [symbolic] |
| | Copper ion is identified to be in the cathode beaker [symbolic] |
| | Copper ion has a 2+ charge in the superscript [symbolic] |
| | The subscript [aq] is used to describe the copper ion [symbolic] |
| | Potassium ion (from salt bridge) is identified to be in the cathode beaker [symbolic] |
| | K is used to label the potassium [symbolic] |
| | The potassium ion (from salt bridge) has a positive symbol in the superscript [symbolic] |
| | The subscript [aq] is used to describe the potassium ion (from salt bridge) [symbolic] |
| | A positive sign is used to label the cathode [symbolic] |
| | The cathode ion goes from solution onto the cathode [symbolic] |
| | Reducton occurs at the cathode and the reduction reaction is written [symbolic] |
| | Electrons go into the cathode [symbolic] |
| **Salt Bridge** | The salt bridge is identified as KNO3 [symbolic] |
| | The negative ion goes from the salt bridge into the anode beaker (NO3-) [symbolic] |
| | The positive ion goes from the salt bridge into the cathode beaker (K+) [symbolic] |
| | The salt bridge has ions [symbolic] |
| **Light Bulb & Wire** | There is something connecting the anode and cathode (wire) [macro] |
| | There is a lightbulb or voltmeter in the middle of the wire [macro] |
| | The light bulb is lit to indicate a flow of electrons [macroscopic] |
| | Electrons flow from left to right [symbolic] |
| | Electrons flow through whatever is connecting the two half cells (wire) [symbolic] |
| **Misc.** | The net reaction of the redox process is written out [symbolic] |

## Chapter 3.1.1 Assessing Understanding of Pre-Lived Object

During phase one of the interview, there were many instances where what students provide in their drawings may not fully encompass what student provide in their oral descriptions. For example, Student MR was able to discuss oxidation and reduction within the narrative, but did not include the presence of metal ions, electrons, or the equations involved in oxidation and reduction in the drawing (Figure 6).

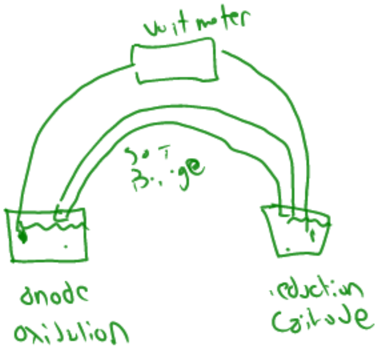
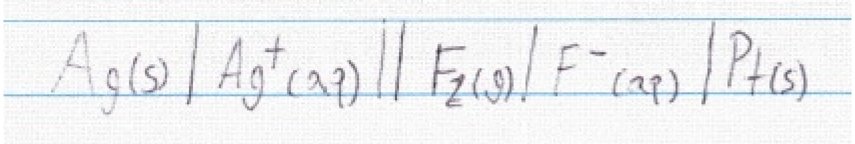


**Figure 6:** Student MR Pre-Lived Object of Learning

> Student MR: Okay so um...initially I'm drawing the um...anode and this is where the ox-um...this is anode and this is where the oxidation takes place. Oxidation place...it takes place and the other side is the uh cathode oops. And this is where the reduction-the reduction takes place.

Student MR certainly acknowledged the roles that oxidation and reduction seem to play within the voltaic cell. When probed further, Student MR was able to discuss the transferring of electrons that was taking place and the consequential charge buildup on each respective side as the voltaic cell proceeds. However, Student MR represent the conceptions with any visual examples. Instances such as redox equations, the showing of ions gaining or losing electrons, or the direction of where the electrons would travel as a result of being loss or gained were all absent from the student's initial drawing. As a result, student drawings such as the one produced by Student MR were not entirely reflective of their understanding as shown by their descriptions being more detailed when compared to their diagrams. It is important to delineate that student drawings do not necessarily measure student understanding of a particular chemical process associated with the voltaic cell. Instead, student drawings only indicate the level of priority to which students assign particular features and thus is indicative of the overall saliency of those features in the student's model. If students potentially do not see the value or relevancy as much as the features that were provided, this may indicate that students do not see the importance of the conceptual model of the voltaic cell and its underlying electrochemistry.

Student DC is another example where a student's commentary was far more detailed than the produced drawing. Specifically, Student DC was able to describe ionic interactions stemming from the salt bridge. Student DC even went so far to comment on where the salt bridge's anion and cation move to their respective destinations. However, in Student DC's initial drawing, he chose to use the shorthand drawing which omitted both the macroscopic representation of a salt bridge and its corresponding symbolic ionic movement (Figure 7).



$Ag_{(s)} | Ag^{+}_{(aq)} || F_{2(g)} | F^{-}_{(aq)} | Pt_{(s)}$

**Figure 7:** Student DC Pre-Lived Object of Learning

> Student DC: That is the uh symbolizes the salt bridge. For that I…I don't know it's um…if it's because that's the symbol that was chosen to represent it but uh I've also seen that the salt bridge is…connect the um the cathode side and the anode side of the electrochemical cell. And they um they're also in between them. So um I guess if you were trying to memorize what it was or what it does then I think that symbol really fits the…really fits it well to what it is in an actual cell.
>
> Interviewer: Okay. Cool. What's the purpose of the salt bridge?
>
> Student DC: Um…it's to um deliver um cations and um anions to different parts of the cell where uh cations go to the cathode and anions go to…towards the anode.

As shown with Student DC, student conceptions can certainly extend much further than what their drawings can suggest. Although the student was able to communicate the idea of ions moving to certain regions of the voltaic cell, the student nevertheless did not include these features in the drawing for several reasons. Perhaps Student DC had felt that the notation utilized for the salt bridge was sufficient by itself. Or perhaps Student DC chose not to prioritize the inclusion of the ionic movement of the salt bridge. There also is the possibility that the utilized notation itself could be limiting what Student DC was portraying because conventionally one would not show associated movement of ions of the salt bridge in this type of representation of the voltaic cell. It was important to note that there was no point throughout this interview where students were rushed. They also had many opportunities throughout the interview to go back and draw any additional features that they wanted to further include. With all of this in consideration, it was an interesting phenomenon that although students such as Student MR and Student DC could be fully capable of describing certain chemical processes of the voltaic cell, they nevertheless chose not to visually represent these chemical processes even when sufficient information had been conveyed orally. As a result, it was insufficient to gauge student understanding solely from their drawings. Shown through their discourse, participants such as Students MR and Student DC were very capable of successfully describing chemistry phenomenon even if their drawings lacked the corresponding visual elements. About 59% of the interviewed students exhibited this trend where their descriptions exceeded their drawings in the level of detail. Primarily, topics that were frequently described by not illustrated included ionic movement of the anode, cathode, and salt bridge, electronic movement, specific labeling of ions or metals with symbolic notation, oxidation and reduction, and few macroscopic elements such as a lit light bulb. Many of these topics mentioned by students were related to symbolic and submicroscopic levels of representation, indicating that students potentially were more comfortable describing these processes with words rather than illustrating them on paper. Because a previous study had shown that it is important for students to be able to engage with science concepts across different modes such as viewing a representation and producing a drawing in order to have a more enriched learning experience (Prain, Tytler, & Peterson, 2009), students should have the capability to couple their drawings with their descriptions without neglecting one or the other.

## Chapter 3.1.2 Alternative Conceptions in Student Prior Knowledge

When students were asked to explain why certain features of the voltaic cell behaved the way that had formerly described, all 12 students experienced a great deal of difficulty in terms of their reasoning and thus produced a gamut of alternative conceptions (Table 5). Noting the persistence of these alternative conceptions was already interesting because the students had just received instruction on the voltaic cell prior to the interview. Every interviewed produced an alternative conception when probed to think further. In terms of overall topics, 92% of students provided alternative conceptions with respect to electrons and ionic interactions. In terms of the specific regions, a majority of students demonstrated the most alternative conceptions with regards to the salt bridge category (twelve instances), followed by the anode category (nine instances). The category that had the fewest alternative conceptions was the light bulb & wire (one instance), followed by the cathode category (three instances). However, of the alternative conceptions that are listed in Table 5, many of them were unique in the sense that there were not many instances of students commonly exhibiting the same alternative conception, indicating the individual construction of mental models as suggested by constructivism. There was some overlap in terms of a particular conception, specifically the notion that there only metal ions were present in solution which a total of three students had described. Students provided a large range of conceptions that all varied in subtle ways; nevertheless, these alternative conceptions predominately related to submicroscopic processes as well as other chemical phenomenon such as spontaneity and electronegativity that cannot be readily observed on the macroscopic level.

**Table 5:** Alternative Conceptions in Phase One

| | Anode | Cathode | Salt Bridge | Light Bulb & Wire | Misc. |
|---|---|---|---|---|---|
| **Student AC** | The metal anion will gather onto the anode | | Ions from the salt bridge donate electrons which flow between the two cells | | |
| | | | Cations will go from the cathode beaker into the salt bridge | | |
| **Student LG** | Everything on the anode side is getting oxidized | | Electrons will travel from anode to cathode via the bridge | | Electrons will flow from anode to cathode and then from cathode to anode |
| | | | Using an acid as a source of ions would work for a voltaic cell | | Electricity is required for a voltaic cell (non-spontaneous) |
| | | | Salt bridge anions will donate electrons which flow between the two cells | | |
| **Student AS** | The metal anion will gather onto the anode | | Ions from the salt bridge donate electrons which flow between the two cells | | Ions undergo covalent interactions in solution |
| **Student MR** | There are only metal ions in anode solution | | There are only metal ions in cathode solution | | |
| **Student SD** | | | Electrons will still move in the wire without a salt bridge | | There are only anions and cations from the salt bridge present |

**Table 5:** Alternative Conceptions in Phase One, Continued

| | Anode | Cathode | Salt Bridge | Light Bulb & Wire | Misc. |
|---|---|---|---|---|---|
| **Student SB** | The negative electrode gains the electron | | | | Electrons are provided by the battery |
| | | | | | There are hydroxides involved in the voltaic cell |
| | | | | | Electricity flows in the opposite direction of electron flow |
| | | | | | Chemical energy changes into electrical energy within th voltaic cell |
| **Student NE** | There are only metal ions in anode solution | There are only metal ions in cathode solution | | | |
| **Student TW** | Oxidation involves the release of electrons and air | | | | The right side should be anode and the left side should be cathode |
| **Student QA** | There are only metal ions in anode solution | There are only metal ions in cathode solution | The salt bridge allows ions to go back to the solvent to keep the redox reaction going | | |
| | | | Anions from the salt bridge go to the cathode | | |
| **Student SG** | The anode is just something at the bottom with no wire attached | | Electrons will travel from anode to cathode via the bridge | Only some of the electrons will go through the voltmeter | The solution facilitates electron movement |
| | | | Salt bridge ion charge have something to do with reduction potential | | |

**Table 5:** Alternative Conceptions in Phase One, Continued

| | Anode | Cathode | Salt Bridge | Light Bulb & Wire | Misc. |
|---|---|---|---|---|---|
| **Student RL** | | | | | When ions and metal interact, they exchange electrons<br>Molecules interacting with the metal will cause the metal to rust<br>Electrode selection is based off of electronegativity |
| **Student DC** | | The inert metal cathode serves as a place for reduction to occur | If you remove the salt bridge, the voltaic cell will still work | | There are only anions and cations from the salt bridge present |

Additionally, it was interesting to observe that the types of emergent alternative conceptions that student provided were very reflective of their diagrams as well. For example, Student LG's initial drawing of the voltaic cell was very different from that of the composite image in the sense that it was one container and it lacked a physical salt bridge. As a result, the types of alternative conceptions that Student LG introduced were primarily involved with the salt bridge itself (Figure 8).

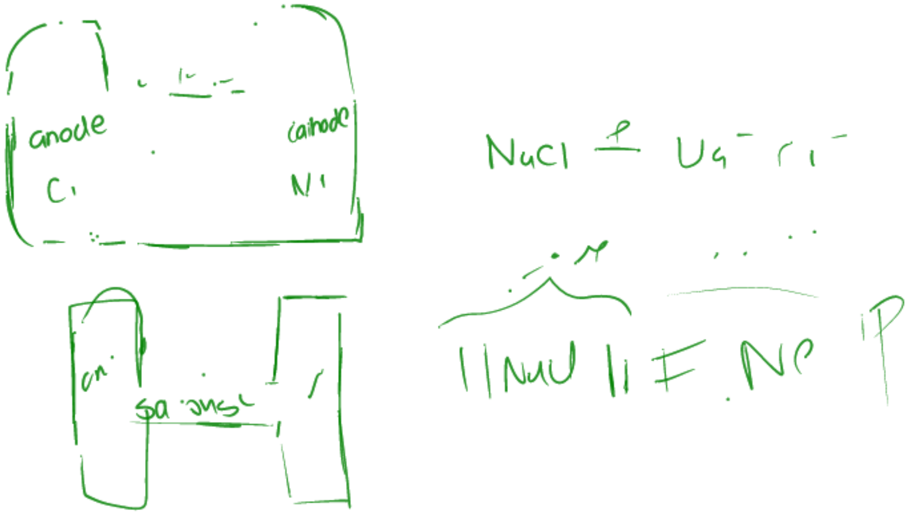


**Figure 8:** Student LG Pre-Lived Object

> Student LG: Yeah. And then I know like...I can't remember what the bridge is called but I know it has to, it has to do with ions.
>
> Interviewer: Okay.
>
> Student LG: And that's how they're able to travel, the electrons.
>
> Interviewer: So the electrons are able to get from anode to cathode via the bridge?
>
> Student LG: Yes. The bridge over [drawn in the middle of the anode and cathode].

Because the drawing of the voltaic cell was a student artifact, it was logical to conclude that the student-produced drawing would be part of the construct that students such as Student LG and Student DC had with regards to electrochemistry. As a result, because of the nature of the salt bridge in their diagrams being scientifically inaccurate, it was reasonable to find that there would be many alternative conceptions with regards to this particular feature of the voltaic cell. Although it was difficult to assess whether it was due to students' prior knowledge that influenced their drawing or whether their drawing affected their mental model of the salt bridge's role, it was nevertheless evident that student prior knowledge and resultant conceptions have a dynamic relationship with his or her generated visual drawing.

Another example of a unique alternative conception introduced during Phase One of interview was shown through what Student RL had discussed (Figure 9). Student RL had just described molecules in solution colliding with the metal to which I asked what she would expect to see as a result of such reaction.

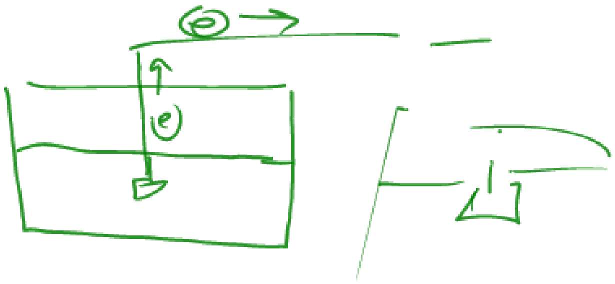


**Figure 9:** Student RL Pre-Lived Object

> Interviewer: And how would you imagine [the ions] interacting with the metal as you just mentioned before?
>
> Student RL: Uh collisions?
>
> Interviewer: Okay and then when they collide, what happens then?
>
> Student RL: Hmm maybe some kind of like…hmm…I don't know…like there's just like…rusting going on maybe.

Although student drawings such as the one belonging to Student RL consisted primarily of macroscopic features, they introduced conceptions that extended beyond what their drawings had included. In this particular case, Student RL had brought up the phenomenon of rusting which was a conception that did belong in the concepts of the voltaic cell itself. Observing the student's adaptation of rusting, a concept relatable to redox reactions, to the voltaic cell, another concept that also incorporated redox reactions, was very indicative of how students construct additional knowledge within their mental scaffolding whether or not such combination would be correct. For Student RL, rusting and the voltaic cell were lumped together as one coherent thought potentially because both are related to redox reactions in theory but not in application. Thus, the chemistry that students described occurring within the voltaic cell had a very interesting relationship with their artifacts. On one hand student conceptions can be very restricted by what was presented as their model of the voltaic cells as in the case of Student LG. On the other hand, student can also contribute alternative conceptions beyond what was presented directly from their voltaic cell drawing as in the case of Student RL.

## Chapter 3.2 Phase Two: How Students View a Representation

As a subsection of this study, an eye tracker was utilized to evaluate how students interacted with the composite image of the voltaic cell representation that was shown to them during the second phase of the interview. The reason that an eye tracker was conducted for just three case studies was due to time constraints as the eye tracker and training became available at a much later time. Furthermore, there were initially some technical difficulties resulting from authentication software not functioning as intended. Due to the time frame of this study, additional data collection would have been highly infeasible once the eye tracker had become functional.

### Chapter 3.2.1 Student RL Eye Tracking Data

When examining Student RL's gaze path (Figure 10), the student's initial adjustment period began by starting right at the center of the voltaic cell representation as shown by the green dot. The student then navigated up towards the light bulb (as shown by the red dots) and went from left to right to the cathode side and swung down, to the left, up, and across the salt bridge (as shown by the blue dots). The student then revisited the light bulb once again, went to the left and all the way down to the reactions (as shown by the yellow dots) and then back to the salt bridge (as shown by the green dots). The student's gaze path eventually terminated by going upwards from the salt bridge to the light bulb in a final instance (as shown by the purple dots).

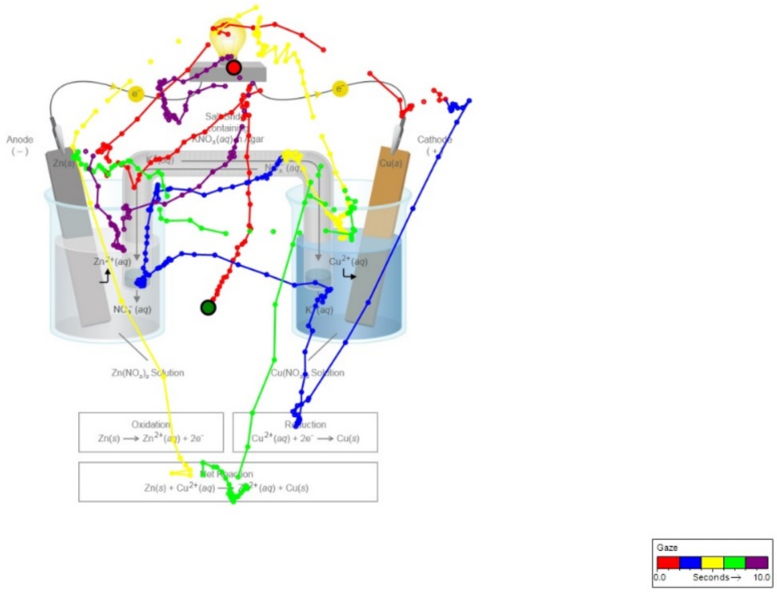


**Figure 10:** Student RL Gaze Path

From Student RL's gaze path, it was determined via comparison that the student was spending a majority of that initial ten seconds viewing at features that were initially absent from the student's drawing (Figure 9). More specifically, Student RL scanned the salt bridge, the reactions, and the light bulb, all of which were initially omitted from the initial drawing. Overall this was a very good application of variation theory. For learning to take place, there has to be a contrast between what is and is not, in this case how the enacted object was different from the Student RL's drawing. Furthermore, Student RL within the first ten seconds did a very general sweep of the voltaic cell. There were no particular features that were not viewed by Student RL. The student also applied general reading conventions in the manner which she viewed the voltaic cell, specifically reading left to right and top-down.

Student RL's fixation data allowed further inspection in terms of what exactly the student was attending to and to what extent throughout the interview (Figure 11).

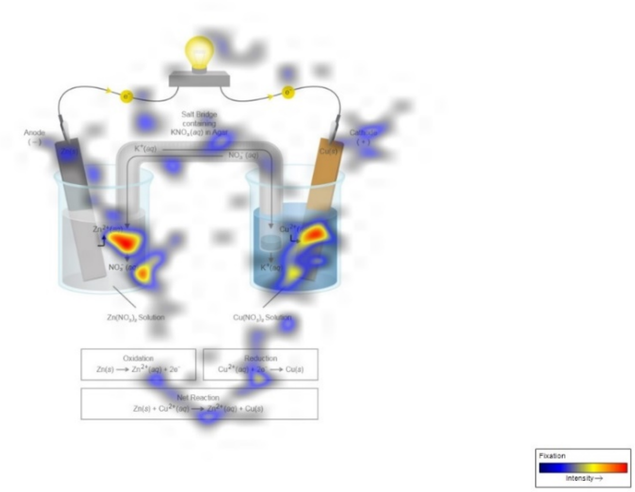


**Figure 11:** Student RL Fixation Heat Map

An initial analysis revealed that most of Student RL's time was spent examining the anode and cathode solution regions, more specifically the regions that encompass a lot of symbolism related to ionic movement from the anode, cathode, and salt bridge. These symbolic features were noticeably absent from Student RL's pre-lived object (Figure 9). In addition, there were warm color indications at the reactions region and the salt bridge region, although both of these examples were not as intense as the anode and cathode regions. Overall, Student RL, similarly to what had been demonstrated through the gaze path, viewed the entire enacted object of learning where almost every part of the voltaic cell had some color attributed to it.

Because Student RL spent a great deal of time looking at the anode and cathode solutions, one potential hypothesis was that Student RL was evaluating certain features and trying to make sense of what was going on. There could be instances of cognitive overload taking place because of the abundance of symbolic chemical processes (such as ionic movement or salt bridge ions interacting with the metal) occurring which could account for the larger portion of time Student RL spent at these specific regions. Student RL could have also spent more time on these regions because they contained a greater amount of symbolic detail than what the student's initial drawing had exhibited. More time could have been spent as a means of processing additional information into Student RL's working model.

### Chapter 3.2.2 Student DC Eye Tracking Data

The gaze path of Student DC had shown that the student first attended to the upper portion of the cathode side of the voltaic cell, specifically between the salt bridge and the wire with the light bulb (Figure 12). Student DC then looked towards the anode portion of the voltaic cell where the student scanned the portion of the salt bridge submerged in anode solution as well as the anode and cathode solution labels at the bottom (as shown by the red and blue dots). The gaze was then shifted up towards the light bulb and swept across the salt bridge (as shown by the blue and yellow dots). The student then looked at the cathode portion of the voltaic cell, specifically at the tip of the salt bridge that was submerged in the cathode solution. Via the purple dots, the student towards the last moments of the initial ten second interval again looked at the salt bridge portion on the anode side as well as the labels for the anode and cathode solution.

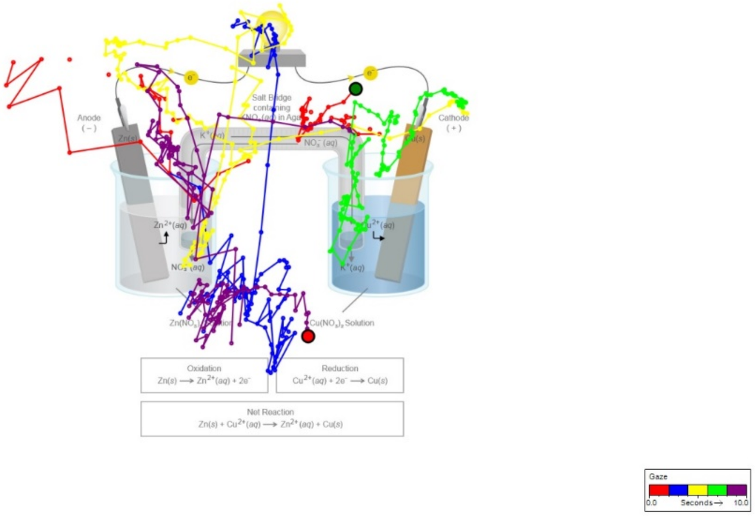


**Figure 12:** Student DC Gaze Path

Similarly to Student RL, Student DC primarily looked at features that were not included in the student's initial drawing (Figure 7). Student DC's initial drawing was essentially the symbolic version of the voltaic cell that lacked the macroscopic features. More specifically, Student DC's shorthand version of the voltaic cell conveyed mostly symbolic features with regards to ion and metal identity and lines that may be indicative of the student acknowledging different phases in the voltaic cell. As shown by the gaze path, Student DC viewed the macroscopic features that were absent in the initial drawing: the salt bridge, the light bulb and wire, the labels of the solution, and the anode and cathode solutions that overlapped with the salt bridge. It appears as if Student DC was attending to specific features of the salt bridge that shed light on the solution chemistry between salt bridge and solution such as ion identity, direction of flow, and solution composition. Furthermore, according to the gaze path, Student DC did not view the anode or cathode as well as the reactions within the initial ten seconds. Although Student DC may not have viewed at the electrodes within the initial ten seconds because they were earlier identified in the student's drawing, it was interesting that the student did not view the reactions within this time frame. Such a case may have been a result of the student regarding the reactions found at the bottom to be less important than the rest of the voltaic cell upon initial exposure to the enacted object of learning.

According to the fixation layer, the areas with the warmest colors were the light bulb and wire, specifically around the top of the cathode (Figure 13). There was no indication of sustained attention to features such as the anode and cathode regions, the salt bridge, or the reactions at the bottom.

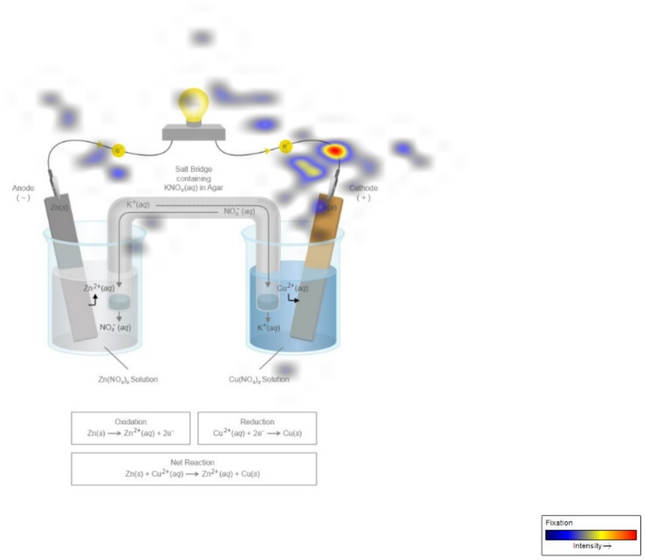


**Figure 13:** Student DC Fixation Heat Map

On one hand, it seems appropriate that Student DC would primarily focus on a feature that was absent from the previously produced drawing. It may have been likely that Student DC was not as familiar with the light bulb and wire. During the assessment of prior knowledge of Phase One, Student DC conveyed many alternative conceptions with regards to the anode, cathode, salt bridge, and ions. There were no alternative conceptions mentioned with regards to the light bulb and wire because the student did not describe this particular feature with much detail. The lack of discussion on the light bulb and wire during Phase One may have been indicative of Student DC not having the same amount of confidence in describing this feature compared to the others that were mentioned or illustrated.

It was surprising to see that Student DC did not fixate on features that were absent from Phase One's drawing such as the salt bridge or the reactions as much relative to the light bulb and wire. This could be the result of two potential scenarios: 1) the student either did not prioritize these features as much as the wire and light bulb or 2) that the student was more familiar with the other features relative to the light bulb and wire. In the first scenario, Student DC may have neglected these features because they were maybe unimportant for the representation of the voltaic cell. In the second scenario, Student DC may have not viewed the rest of the features due to pre-existing familiarity with that information that was not conveyed in the produced drawing of Phase One. Although Student DC did not include these features within the previous drawing, such omission at that moment of time perhaps was less indicative of a lack of understanding but more so a lack of relevancy attributed to said features. In terms of Student DC's fixation data, it was interesting to note that the particular region that had the warmest color indication was the area surrounding the wire right above the cathode. Not as much time was spent looking at the same portion on the anode end. The increased time spent on the top portion of the cathode side may have resulted from the student evaluating the wire and the light bulb. As shown when prompted to discuss the enacted object of learning, Student DC had mentioned about how he found the light bulb to be confusing.

> Interviewer: Okay. Is there anything you find to be confusing about this representation?
>
> Student DC: Uh I would say um I guess the light bulb.
>
> Interviewer: What about the light bulb is unclear?
>
> Student DC: Um I don't know I…[inaudible] I'm just used to seeing uh like a voltmeter or something like that.

Thus, the manner in which Student DC fixated upon the wire and the light bulb could be due to a combination of two reasons: the fact that the light bulb and wire originally was omitted from the initial drawing and that the student did not quite understand the usage of a light bulb. However, why the cathode side of the light bulb and wire was considerably viewed for a much longer duration remained unclear.

### Chapter 3.2.3 Student QA Eye Tracking Data

Student QA had brought the initial drawing and had placed it for reference in the bottom right had corner of the monitor which had potentially caused eye tracker to register the eye movements outside of the boundaries initially set. Consequently, it was necessary to adjust some of the eye tracking data, specifically the fixation data, by transforming it along the x-axis and y-axis for correction purposes. In other words, the uncorrected version of Student QA's fixation data had shown very warm spots on generally blank areas devoid of any features of the voltaic cell representation.

The fixation layer was thus adjusted to the right and shifted up in order to most reasonably estimate how the student viewed the representation.

Student QA's gaze path of the initial ten seconds of interacting with the enacted object of learning suggested that he had begun at the right portion of the screen (most likely from glancing at the pre-lived object initially) and immediately looked towards the light bulb and broadly swept across the anode portion of the voltaic cell, looking specifically at the anode solution as well as the salt bridge submerged within the anode (as shown by the red and blue dots) (Figure 14).

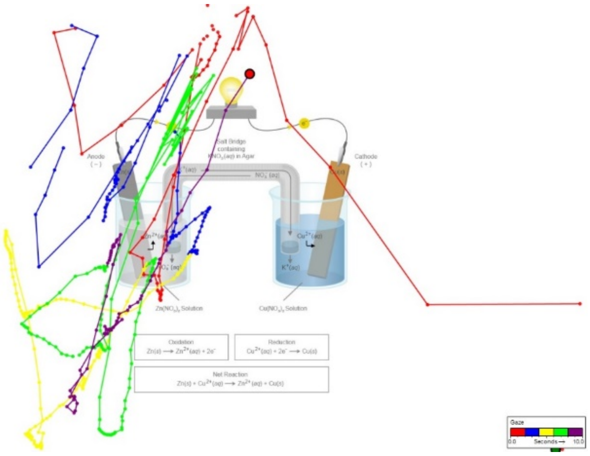


**Figure 14:** Student QA Gaze Path

Afterwards, the student kept scanning strictly the cathode side (as shown by the yellow and green dots) and eventually navigated to the light bulb where Student QA's gaze had ended (as shown by the purple dots). Student QA spent the initial ten seconds by examining the anode side specifically while not viewing the cathode side. This could have resulted from the initial realization that Student QA had accidentally swapped the electrode identities.

> Student QA: Yeah. Okay the zinc and copper I mixed them up just now so yeah. Like I flipped it around.

As the student had followed standard reading conventions by examining left to right, it made sense that the student would note the discrepancy on the anode side first as it was on the left side of the representation.  It was also worth noting that the red line of the gaze path that veers far to the right may have been an instance where the student glanced at the prior drawing that was adjacent to the computer monitor, thereby causing the eye tracker to note that the student had viewed something very close to the sensor limitations.  This could potentially explain why the student had apparently shifted the gaze to a largely empty space devoid of any particular features.

Similarly to that of Student RL, Student QA's fixation layer had indicated that a great deal of time was spent observing the portion of the anode and cathode solutions that incorporated a lot of symbolism with regards to ion identity, movement, and interaction with regards to the salt bridge or electrode (Figure 15).

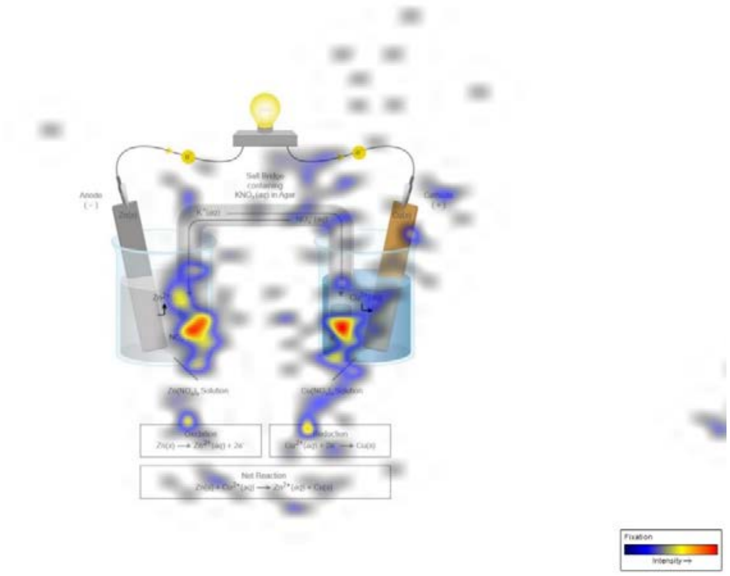


**Figure 15:** Student QA Fixation Heat Map

Student QA also fixated on the formulas, more so on the oxidation and reduction formulas specifically. According to the heat maps, more time was spent on the cathode as well as the region between the salt bridge and the rightmost wire relative to other areas of interest in the representation. The intensity spent on the solution regions of the anode and cathode was indicative of similar reasoning shown through Student RL. Firstly, more time spent on these regions may implicate mental processing and cognitive overload. Because multiple features and processes took place within this region; the student could have spent time examining these portions as a means of evaluating what was going on since the student's pre-lived object lacked the symbolism of the ions from the salt bridge. On the other hand, the student could have already understood the concepts related to the solution chemistry found within these regions. The time spent here could have been a reaffirmation of what the student already knew as Student QA began to reorganize the priorities certain features have within the student's model of the voltaic cell. Regardless, it seemed that these portions of the voltaic cell in which Student QA spent the most time viewing was potentially indicative of the relative importance these features possessed in the student's model at this moment of time.

Overall, the fixation data had revealed the amount of time in percentages that Students RL, DC, and QA spent viewing the representation of the voltaic cell, the numbers of which are summarized below (Table 6).

**Table 6:** Summary of Fixation Data of Case Studies

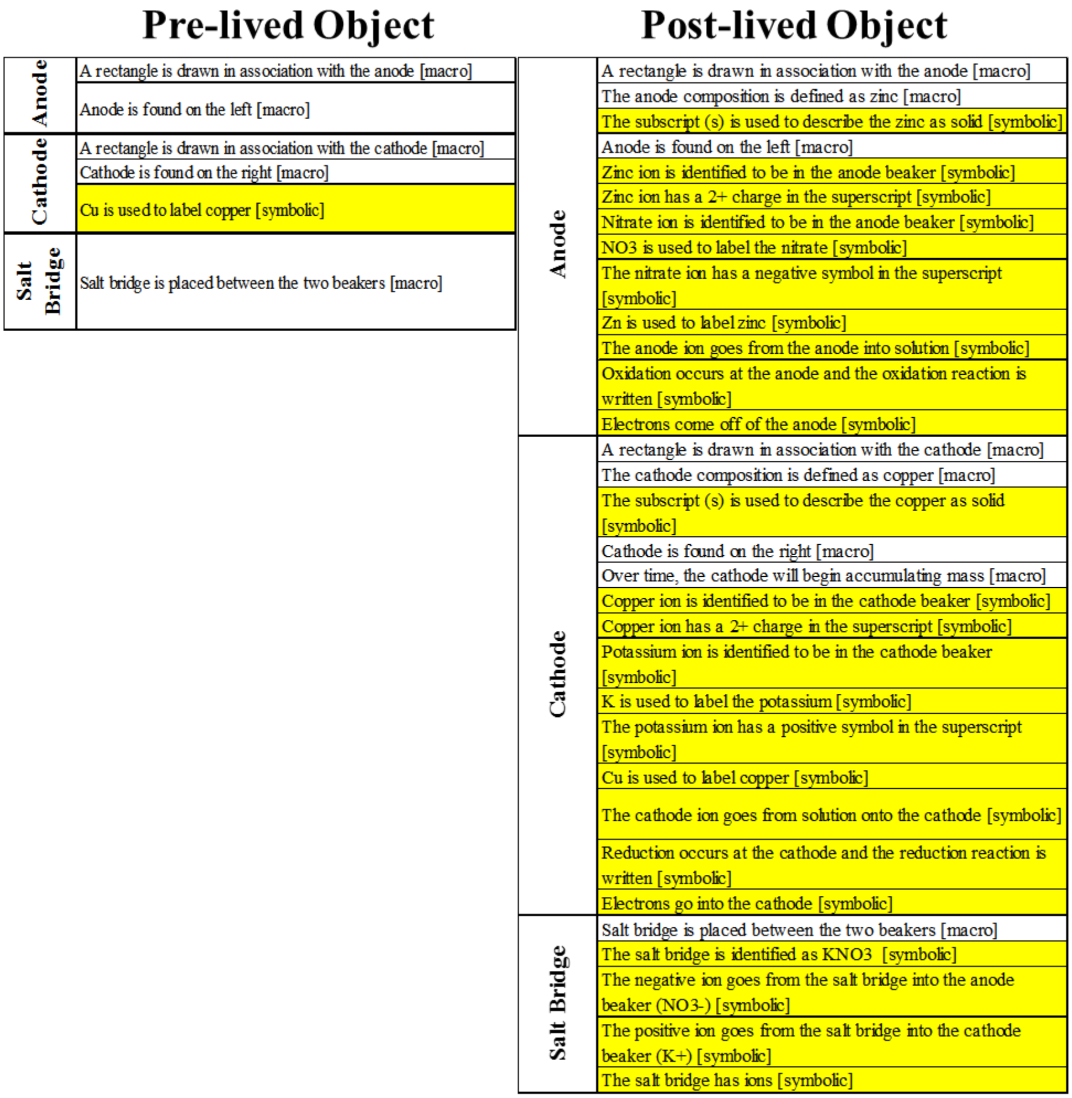
| | **Anode** | **Cathode** | **Salt Bridge** | **Light Bulb & Wire** | **Reactions** |
|---|---|---|---|---|---|
| **Student RL** | 28.8% | 27.9% | 11.5% | 4.7% | 12.4% |
| **Student DC** | 1.7% | 1.7% | 1.7% | 58.6% | 0.0% |
| **Student QA** | 27.8% | 25.3% | 7.9% | 7.9% | 5.9% |

Variation theory aims to capture the range of experiences that students may undergo within a learning event. In this case, the three students all uniquely viewed the representation with different amounts of time allocated to each region. Specifically, Student RL and Student QA spent more time on the anode and cathode regions relative to the other regions while Student DC spent more than half of the time on the light bulb & wire region. With the exception of Student RL, the reactions region also was not viewed as much. The variation in how the students viewed the representation, due to a range of factors such as prior knowledge, importance to the student, or contradictions against their mental models, nevertheless affirms the claim that students can experience a learning event in entirely different ways despite being shown the same representation.

## Chapter 3.3 Phase Three: Evaluating Post-Lived Object of Learning

Student’s post-lived objects had shown a dramatic increase in macroscopic and symbolic features in the anode, cathode, salt bridge, light bulb and wire, and the miscellaneous categories (Table 7). Included symbolic features were highlighted in yellow. In addition, the features that the majority included in their pre-lived objects of learning are also included on the left for comparison purposes.

**Table 7:** Features that a Majority Included in Post-Lived Object



**Pre-lived Object**

| | |
|---|---|
| **Anode** | A rectangle is drawn in association with the anode [macro] |
| | Anode is found on the left [macro] |
| **Cathode** | A rectangle is drawn in association with the cathode [macro] |
| | Cathode is found on the right [macro] |
| | Cu is used to label copper [symbolic] |
| **Salt Bridge** | Salt bridge is placed between the two beakers [macro] |

**Post-lived Object**

| | |
|---|---|
| **Anode** | A rectangle is drawn in association with the anode [macro] |
| | The anode composition is defined as zinc [macro] |
| | The subscript (s) is used to describe the zinc as solid [symbolic] |
| | Anode is found on the left [macro] |
| | Zinc ion is identified to be in the anode beaker [symbolic] |
| | Zinc ion has a 2+ charge in the superscript [symbolic] |
| | Nitrate ion is identified to be in the anode beaker [symbolic] |
| | NO3 is used to label the nitrate [symbolic] |
| | The nitrate ion has a negative symbol in the superscript [symbolic] |
| | Zn is used to label zinc [symbolic] |
| | The anode ion goes from the anode into solution [symbolic] |
| | Oxidation occurs at the anode and the oxidation reaction is written [symbolic] |
| | Electrons come off of the anode [symbolic] |
| **Cathode** | A rectangle is drawn in association with the cathode [macro] |
| | The cathode composition is defined as copper [macro] |
| | The subscript (s) is used to describe the copper as solid [symbolic] |
| | Cathode is found on the right [macro] |
| | Over time, the cathode will begin accumulating mass [macro] |
| | Copper ion is identified to be in the cathode beaker [symbolic] |
| | Copper ion has a 2+ charge in the superscript [symbolic] |
| | Potassium ion is identified to be in the cathode beaker [symbolic] |
| | K is used to label the potassium [symbolic] |
| | The potassium ion has a positive symbol in the superscript [symbolic] |
| | Cu is used to label copper [symbolic] |
| | The cathode ion goes from solution onto the cathode [symbolic] |
| | Reduction occurs at the cathode and the reduction reaction is written [symbolic] |
| | Electrons go into the cathode [symbolic] |
| **Salt Bridge** | Salt bridge is placed between the two beakers [macro] |
| | The salt bridge is identified as KNO3 [symbolic] |
| | The negative ion goes from the salt bridge into the anode beaker (NO3-) [symbolic] |
| | The positive ion goes from the salt bridge into the cathode beaker (K+) [symbolic] |
| | The salt bridge has ions [symbolic] |

**Table 7:** Representational Features that a Majority Included in Post-Lived Object, Continued

**Pre-Lived Object**

| | |
|---|---|
| **Light Bulb and Wire** | There is something connecting the anode and cathode (wire) [macro] |
| **Misc.** | Electrons are represented as e- [symbolic] |
| | There are two containers representing the two half cells |
| | Liquid is found within the container [macro] |

**Post-Lived Object**

| | |
|---|---|
| **Light Bulb and Wire** | There is something connecting the anode and cathode (wire) [macro] |
| | There is a lightbulb or voltmeter in the middle of the wire [macro] |
| | Electrons flow from left to right [symbolic] |
| | Electrons flow through the wire [symbolic] |
| **Misc.** | Electrons are represented as e- [symbolic] |
| | There are two containers representing the two half cells [macro] |
| | Liquid is found within the container [macro] |

In particular, student drawings in Phase Three incorporated much greater symbolic details with respect to the anode, cathode, and salt bridge regions. The regions that saw the greatest difference in change were both the cathode and anode, both of which had 11 features that were newly incorporated. Of the newly included features, 10 were symbolic for both the anode and cathode regions as well. In total, a majority of the population identified and included 39 critical features. Alongside with additional features being incorporated in student drawings, there were instances where students also provided additional conceptions previously absent during Phase One. For example, Student SD was asked to provide commentary on the rationale behind including the reduction and oxidation equations in the subsequent drawing of the voltaic cell drawing.

> Interviewer: And why did you decide to include those things this time around?
>
> Student SD: Mm...I think that the formula can better explain the oxi- the like the oxidation and how-how to how this two forms together. And this one...this is...just more explanation about how...about what's the reaction in this-in uh in this bottle

In another example shown with Student NE, this student was asked to provide an analysis of why certain conventions were utilized when it comes to the assigning to negative and positive symbols to the anode and cathode respectively.

> Student NE: So I've know that for the anode is part of uh...oxidation reaction...that's what it relates to. And negative is the loss of electrons. And cathode relates to reduction. And it's the gain of electrons so it's positive.

Shown in participants such as Student SD and NE, it was noted that students would introduce both new conceptions and features in Phase Three. These emergent conceptions that justified why certain features were newly included were likely to have been derived from student prior knowledge. The reason was that the composite image shown to students lacked any information regarding why features were presented in that particular manner. In addition, I as the interviewer would avoid inputting any additional information as strictly as possible so as not to bias or influence the students' models. Because it was more probable that these conceptions, absent from Phase One but conveyed in Phase Three, originated from the student's prior knowledge, there was the implication that the voltaic cell representation shown to students in Phase Two may be effective at cueing students to think in a particular manner. Additional information associated with features could potentially resurface, thereby suggesting that the voltaic cell representation in effect could instigate a reordering of importance within students' mental models within that particular moment. Potentially, students could have responded to the voltaic cell representation in a manner they deemed appropriate for this study (i.e. trying to reproduce the answer they think I wanted to hear). Because there were so many symbolic details included in the voltaic cell representation, students may have treated these symbolic features were greater priority and may have felt compelled to include these symbols in their subsequent drawings so as to satisfy whatever requirement they felt needed to have been fulfilled for this study. Students may also think that the representation shown to them served as a “correct model,” suggesting that the all of the features exhibited in that particular representation were necessary for the reproduction of a representation of the voltaic cell. This reasoning may have also cued students to think in a manner that made symbolic features more necessary than they initially were in the students’ prior drawings. In other words, students after Phase Two may now potentially feel certain features to be more salient for voltaic cell discussion at that moment of time, revealing a more dynamic mental model that could be adjusted and appended with information from both prior knowledge as well as external factors such as the voltaic cell representation. As a result, the omission of features and conceptions in Phase One does not necessarily suggest that students lack understanding but rather that students prioritize certain features of the voltaic cell more so than other features. Furthermore, whether it was describing what would happen to the voltaic cell visually over time or explaining why previously absent voltaic cell features were now included, it was observed that students were capable of extending their conceptions beyond what was possibly interpretable strictly from the enacted object of learning.

Because this study had shown that student mental models could be subject to situational modification via the increase in both symbolic details and student conceptions for post-lived objects, the implications for teaching are that the visual representation of the voltaic cell should be judiciously used in curriculum. The voltaic cell representation has been observed to cue students to think in a particular manner, and so it is necessary to anchor students in the critical features of the voltaic cell representation so that the intentions of the instructor for what students should learn can be better achieved. Otherwise, because of how dynamic student mental models are, exposure to voltaic cell representations may lead to alternative conceptions where information unintended by the instructor is incorporated. The persistence of alternative conceptions could prevent the student from accurately understanding the voltaic cell and its underlying electrochemistry.

### Chapter 3.3.1 Alternative Conceptions in Post-Lived Object

Just as how the visual representation of the voltaic cell can prompt students to input additional scientifically accurate conceptions as shown previously, visual representations can also cue students to convey alternative conceptions (Table 8). Of the 12 interviewed students, 100% exhibited alternative conceptions in their post-lived objects. The greatest number of alternative conceptions were associated with the salt bridge and miscellaneous categories (nine instances for both). The anode and cathode categories had approximately equivalent amounts of alternative conceptions (six and five instances respectively). The category that had the fewest alternative conceptions was the light bulb and wire (two instances). In general, student alternative conceptions predominantly dealt with the submicroscopic processes of electronic and ionic interactions found throughout the voltaic cell. Furthermore, there was no observable overlap in terms of consistent alternative conceptions among students; all of the alternative conceptions described by the interviewed students were predominantly nuanced and unique in their individual ways. Only 25% of the students exhibited persistent alternative conceptions that were both present in Phase One and Phase Three, mostly encapsulating concepts relating to the salt bridge and its corresponding ions as well as other underlying electrochemistry concepts. These findings align well with constructivism and variation theory. Students are constructing their conceptions in real time as shown by the appearance of alternative conceptions that were previously absent in Phase One. In addition, a large range of different interpretations of the voltaic cell was observed which potentially signifies that students experienced the voltaic cell in a variety of different ways.

**Table 8:** Alternative Conceptions in Post-Lived Object

| | Anode | Cathode | Salt Bridge | Light Bulb & Wire | Misc. |
|---|---|---|---|---|---|
| **Student AC** | | | The amount of charge per ion has an effect on the voltaic cell | | Anions bring electrons through the wire to the light bulb |
| **Student LG** | There is no metal loss seen on the anode | | Electron movement is not a one way thing<br>The wire is connected to the salt bridge<br>Electrons flow back to the anode through the salt bridge | | Electrons will flow from anode to cathode and then from cathode to anode<br>Electricity is required for a voltaic cell (non-spontaneous) |
| **Student AS** | | | NaCl provides two electrons instead of one | | |
| **Student MR** | The term anode refers to the whole side of the cell | The term cathode refers to the whole side of the cell | | | |
| **Student SD** | | | Electrons flow back to the anode through the salt bridge | | Ions undergo covalent interactions in solution |
| **Student SB** | | | | | Electrons flow from right to left (opposite direction of electricity)<br>The voltaic cell now involves a hydrolysis reaction with hydrogen and oxygen<br>The water in the container will run out as time goes on as a result of the reaction |
| **Student NE** | The electrolyte solution strips the electron off of the anode | | | | Neutrality is maintained to keep the ions from reacting with anything else |

**Table 8:** Alternative Conceptions in Post-Lived Object, Continued

| | Anode | Cathode | Salt Bridge | Light Bulb & Wire | Misc. |
|---|---|---|---|---|---|
| **Student TW** | The zinc will react with the nitrate first and then give off two electrons<br>The zinc metal will lose color over time | The copper metal will get darker over time | | | |
| **Student QA** | | Nitrate ions on the cathode side will not react with the copper ions | The salt bridge provides ions which then provide electrons to resume oxidation<br>Anions from the salt bridge go to the cathode | | |
| **Student SG** | | | Nitrates from the cathode side travel to the anode side | | |
| **Student RL** | | | | Positive ions flow from right to left through the wire<br>Electrons travel from the metal, through the wire, and end up at the solution | The liquid provides the ions needed for the reaction while the salt bridge is just there to balance |
| **Student DC** | Volume increases | It is faster to use active electrodes rather than inert electrodes<br>Volume decreases | | | Ions in solution are just floating, not interacting with one another |

The data from Phase Three has revealed a multitude of alternative conceptions of varying content. For example, there were 9 examples of alternative conception regarding the macroscopic level of representation, one of which was conveyed in Student LG’s interview. In order to clarify what the student had drawn, I had asked Student LG to describe the placement of the wire with regards to the student’s drawing.

> Student LG: I guess...like if you think about it, it'd be wires to something you know? Like a connection for the...like the electricity to flow to light the bulb up.
>
> Interviewer: Mkay, gotcha. So those wires, what are they currently connected to?
>
> Student LG: The...salt...bridge.

Alongside with alternative conceptions dealing with macroscopic features, Table 8 had shown that there were also more alternative conceptions regarding ionic and electronic interactions of the submicroscopic level. Specifically, there were 20 different alternative conceptions dealing with particulate processes of ions and electrons. In one example of an alternative conception with regards to electron movement throughout the voltaic cell, I had asked Student SD to clarify how and where the electrons were traveling within the student’s drawing. Student SD had suggested that electrons in the voltaic cell travel in a circular fashion to which I probed further to ask by what means would electrons be able to achieve such directionality in the context Student SD’s drawing.

> Student SD: Um...[long pause] because the um...I think it is the...it's because in this system there is uh like a circle...circle of...and the if we take apart...take this apart-part of the circle out it will not form a circle. And this just...it just lose its balance.
> […]
>
> Interviewer: Mkay. So you mentioned a circle of this representation...does that mean you have electrons to the anode to the cathode...and then electrons are coming back to the anode as well?
>
> Student SD: Yeah.
>
> Interviewer: Mkay. So how are electrons are getting back to the anode?
>
> Student SD: Mm...this way? Going from the cathode to the anode.
>
> Interviewer: Mmhmm...and how would the electrons do that?
>
> Student SD: Through the salt bridge

In terms of alternative conceptions with ions, one alternative conception was noted during Student NE's interview. During Phase Three, Student NE had initially begun to discuss the topic of neutrality. In response, I had asked Student NE to describe how neutrality was incorporated into the functionality of the voltaic cell relative to the ions found within solution that Student NE had also previously mentioned during the interview.

> Interviewer: Wha-what is neutrality in the context of this voltaic cell? Let's start off easy. Neutrality of what?
>
> Student NE: Um...the ions and solution.
>
> Interviewer: The ions and the solution. Okay. And why do you want to make it neutral?
>
> Student NE: So they're stable.
>
> Interviewer: They're stable?

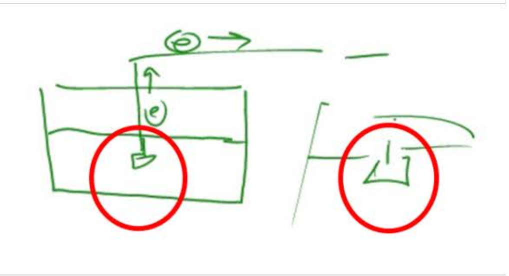
> Student NE: Yeah.
>
> Interviewer: And then it being stable...what kind of effect does that have on the cell?
>
> Student NE: It won't react with anything else.
>
> Interviewer: Okay. So could you explain to me what could happen if you don't make things neutral?
>
> Student NE: Um the other ion-the ions could go into a certain metal. Cause a difference in voltage, I believe.

As shown through the analysis of the interviews conducted with Students LG, SD, and NE, student participants of this study exhibited alternative conceptions that dealt with both macroscopic and submicroscopic features, signifying how there potentially can be a very broad range of alternative conceptions that could emerge after a learning event, specifically after when students viewed the representation of the voltaic cell. Specifically with these three students, it was important to note that the alternative conceptions that they had described during Phase Three were initially absent in their pre-assessment during Phase One. The significance of these newly emergent alternative conceptions relate back to the potential implications of the representation of the voltaic cell. Previously shown in Table 4 of Chapter 3.3, it was likely that the representation of the voltaic cell cued students to incorporate more symbolic features, thereby generating a more detailed voltaic cell representation. Furthermore, it was observed that students were able to provide reasoning for these newly incorporated features, most likely indicating that they possessed the prior knowledge to modify their mental models at that moment. Because these results conveyed a degree of plasticity for student mental models, there is also the potential that student conceptions can be constructed in a non-scientific manner. Thus, when showing students a representation of the voltaic cell, there could potentially exist an unintended effect shown through the number of newly emergent alternative conceptions, the persistence of several alternative conceptions, and the types of alternative conceptions which in this study found to be primarily submicroscopic and macroscopic in nature. As a result, just because students are incorporating additional details in their representations may not signify that they have accurate understanding of the voltaic cell and the chemical processes within. When using the representation of the voltaic cell as a learning tool, instructors should be cautious in its portrayal because of how interpretable the representation can be for students. If an instructor's goal were to promote the understanding of the particulate chemistry within the voltaic cell, the number of features included in a student drawing, as shown by the data of this study, could potentially be an insufficient and at times an inappropriate metric.

### Chapter 3.3.2 Combining Eye Tracking Data

The eye tracking data had suggested a variety of implications with regards to the relationship between how students view the representation and how that may affect their drawings afterwards. One implication was the potential effect that viewing features of a representation of a voltaic cell may have on subsequent student drawings. For example, their fixation data had shown that Students RL and QA had viewed the anode and cathode solutions, specifically the regions that contained many instances of symbolism regarding the metal and salt bridge ions, for a longer period of time relative to the other features present in the representation. Transitioning to Phase Three, Students RL and QA incorporated greater symbolic and submicroscopic details respectively in their post-lived objects (Figure 16 & Figure 17). Shown by the increased details of the post-lived objects belonging to Student RL and QA, it is reasonable to interpret the data that one possibility is if students were to fixate on particular features of the representation of the voltaic cell for a longer duration, it would be likely that these same features would later be incorporated in their subsequent drawings. In terms of Student RL, the post-lived object included symbolic features suggesting the movement and presence of ions, features that were largely absent in the pre-lived object. For Student QA, the post-lived object contained instances of submicroscopic levels of representation which was not even present in the enacted object of learning, potentially signifying that the regions the student viewed the most could have cued the student to think in an entirely different level of representation.

**Figure 16:** Student RL Pre/Post Comparison of Anode and Cathode Regions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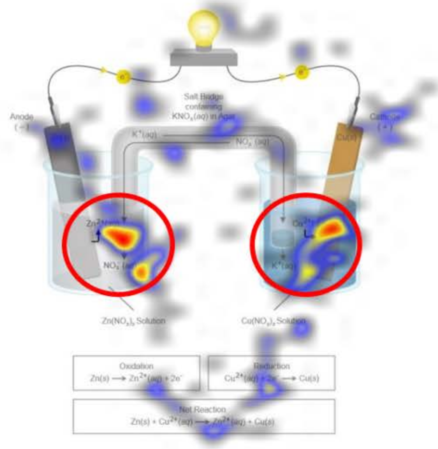

Anode
(−)
Salt Bridge
containing
$KNO_3(aq)$ in Agar
Cathode
(+)
$K^+(aq)$
$NO_3^-(aq)$
Cu(s)
$Zn^{2+}(aq)$
$NO_3^-(aq)$
$Cu^{2+}(aq)$
$K^+(aq)$
$Zn(NO_3)_2$ Solution
$Cu(NO_3)_2$ Solution
Oxidation
$Zn(s) \longrightarrow Zn^{2+}(aq) + 2e^-$
Reduction
$Cu^{2+}(aq) + 2e^- \longrightarrow Cu(s)$
Net Reaction
$Zn(s) + Cu^{2+}(aq) \longrightarrow Zn^{2+}(aq) + Cu(s)$

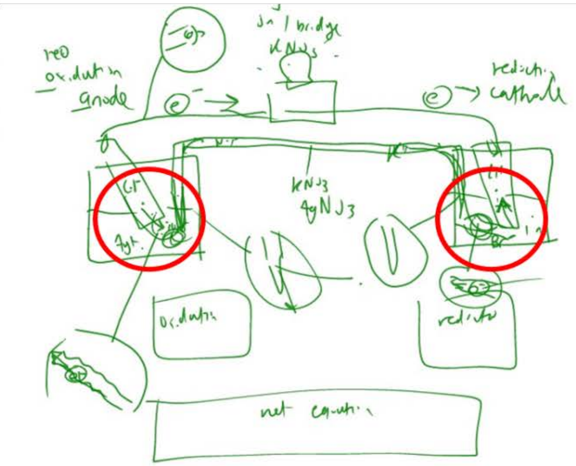
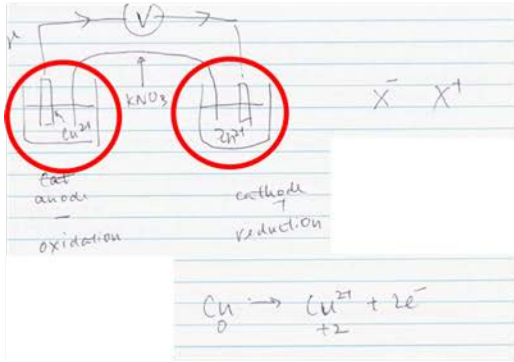
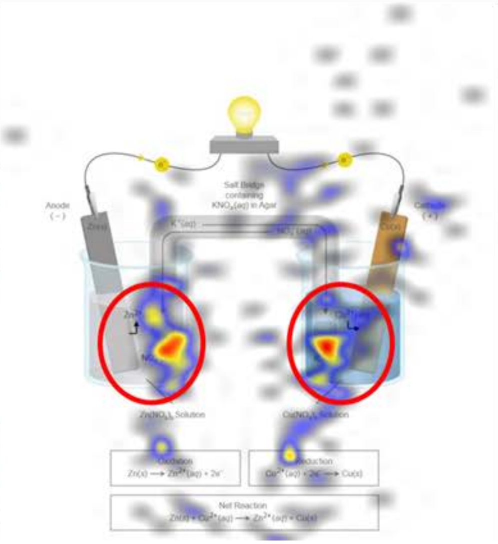
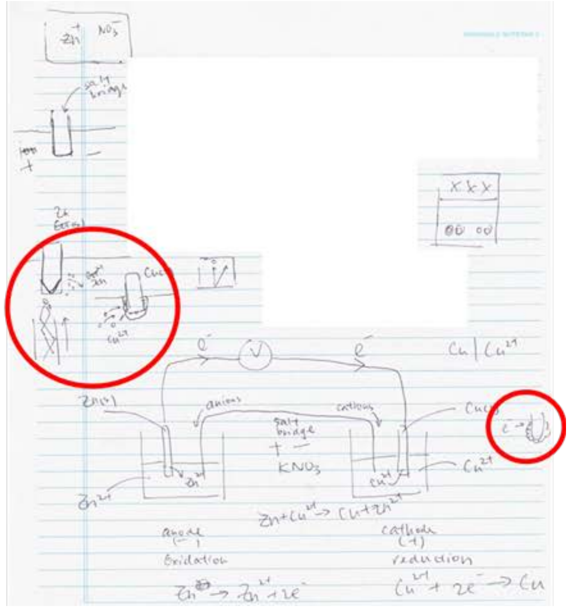

red
oxidation
anode
e⁻ →
salt bridge
KNO3
reduction
e → cathode
KNO3
AgNO3
Cu
Ag
oxidation
reduction
net equation

**Figure 17:** Student QA Pre/Post Comparison of Anode and Cathode Regions

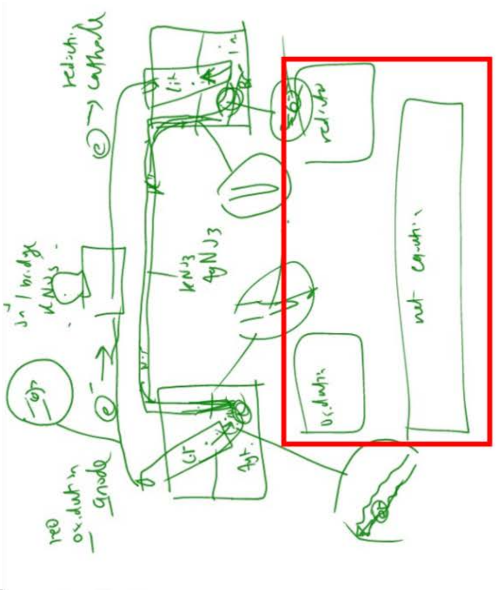

V
KNO3
$Cu^{2+}$
$Zn^{2+}$
$X^-$ $X^+$
cat
anode
−
oxidation
cathode
+
reduction
$Cu \rightarrow Cu^{2+} + 2e^-$
0
+2

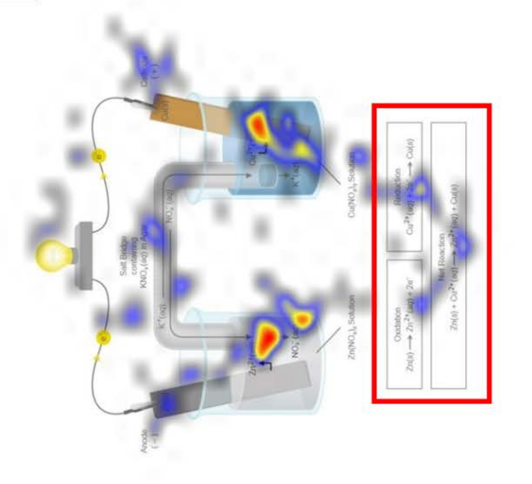

Salt Bridge containing $KNO_3(aq)$ in Agar
Anode (−)
Cathode (+)
Zn(s)
Cu(s)
$K^+(aq)$
$NO_3^-(aq)$
$Zn(NO_3)_2$ Solution
$Cu(NO_3)_2$ Solution
Oxidation
$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$
Reduction
$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$
Net Reaction
$Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s)$


$Zn^+$ $NO_3^-$
salt bridge
XXX
$e^-$
V
$Cu|Cu^{2+}$
Zn(s)
anions
salt bridge
+ −
$KNO_3$
cations
Cu(s)
$Cu^{2+}$
$Zn^{2+}$
$Zn + Cu^{2+} \rightarrow Cu + Zn^{2+}$
anode
(−)
oxidation
cathode
(+)
reduction
$Zn \rightarrow Zn^{2+} + 2e^-$
$Cu^{2+} + 2e^- \rightarrow Cu$

However, there were instances where viewing certain features of the voltaic cell representation for a period of time had a different effect on the students' post-lived objects than previously mentioned. For example, Students RL and DC also spent time viewing the reactions and the wire respectively. According to Table Y, Student RL spent 12.4% of the total time on the reactions which was the third most viewed region according to the student's fixation data. In terms of the region itself, the fixation data suggested that Student RL looked at all three present reactions: oxidation, reduction, and the overall net. This was determined by the blue spots in each of the three reaction boxes found at the bottom of the representation. Similarly, Student DC spent 58.6% of the time viewing the light bulb and wire region, specifically on the right portion of the wire, closest to the cathode. According to this student's fixation data, the light bulb and wire region was viewed the most in terms of overall time spent as shown by the red spot. However, contrary results had appeared when inspecting the post-lived objects of Student RL and Student DC. Student RL in the post-lived object had acknowledged the presence of the reactions by drawing the boxes but did not include the symbolism involved that comprises of the reactions themselves (Figure 18). Instead, Student RL simply titled the boxes as "oxidation," "reduction," and "net equation" respectively. For Student DC's post lived object, the wire was again omitted and yet this drawing now incorporated additional details of symbolic features within the anode and cathode solution, regions that Student DC only viewed for 1.7% of the total duration (Figure 19).

**Figure 18:** Student RL Pre/Post Comparison of Reactions


oxidation
anode
salt bridge
KNO3
KNO3
AgNO3
reduction
cathode
oxidation
reduction
net equation


Anode
(−)
Cathode
(+)
Salt Bridge
containing
KNO3(aq) in agar
Zn(NO3)2 Solution
Cu(NO3)2 Solution
Oxidation
Zn(s) → Zn2+(aq) + 2e−
Reduction
Cu2+(aq) + 2e− → Cu(s)
Net Reaction
Zn(s) + Cu2+(aq) → Zn2+(aq) + Cu(s)

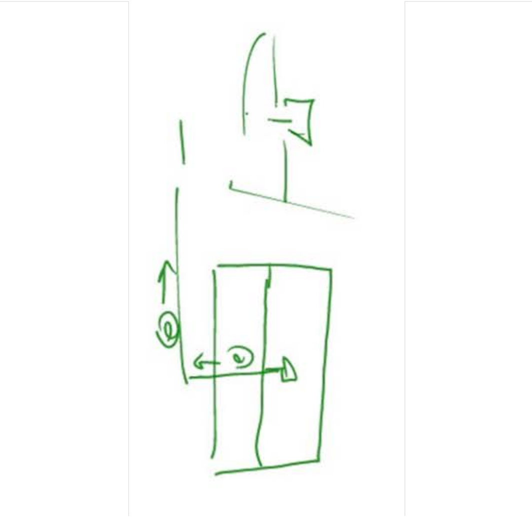
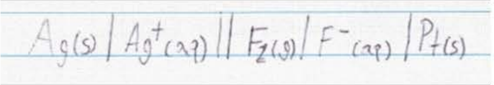
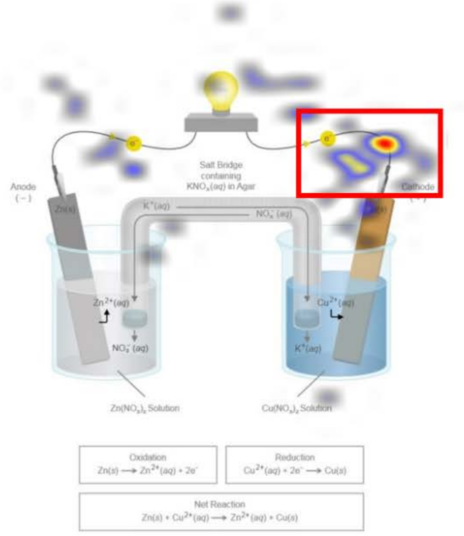

e

**Figure 19:** Student DC Pre/Post Comparison of Wire



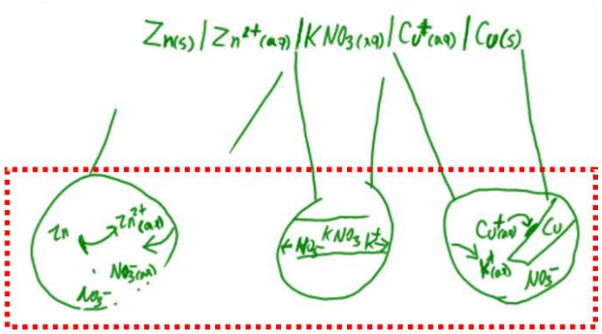
$Ag(s) \mid Ag^+(aq) \parallel F_2(g) \mid F^-(aq) \mid Pt(s)$



Oxidation
$Zn(s) \longrightarrow Zn^{2+}(aq) + 2e^-$

Reduction
$Cu^{2+}(aq) + 2e^- \longrightarrow Cu(s)$

Net Reaction
$Zn(s) + Cu^{2+}(aq) \longrightarrow Zn^{2+}(aq) + Cu(s)$



$Zn(s) \mid Zn^{2+}(aq) \mid KNO_3(aq) \mid Cu^{2+}(aq) \mid Cu(s)$

Because Student RL had omitted the symbolic features of the reactions themselves despite spending time viewing these reactions in the representation, this could potentially be indicative of two underlying reasons. One scenario may be that Student RL spent time viewing and evaluating the reactions of the representation due to a lack of prior knowledge with regards to this particular feature. If Student RL were not familiar with the reactions present in the representation, it would be likely that Student RL would spent more time viewing this particular region as a means of trying to understand what was going on. In the case that Student RL was unable to make sense of the reactions and thus was not able to incorporate these symbolic features in the student's model of the voltaic cell, the notion of leaving the reactions blank but at least acknowledging their presence by providing the titles in the boxes could be a reasonable outcome. The other scenario could be due to the level of priority which the reactions possess in Student RL's model. Although time was spent viewing the reactions of the representation, Student RL may have omitted the reactions due to a lack of relevancy pertaining to what the student felt would be a sufficient drawing of the voltaic cell at that moment of time. Even if the student may have had adequate understanding of the reactions shown in the representation, if the reactions themselves were not salient to what Student RL considered to be important with regards to the voltaic cell, it would be understandable that such a feature would be omitted subsequently. In this instance, Student RL's data comparison had shown that a student spending more time viewing features of a representation may not be indicative of how much priority to which the student would assign those features. Consequently, features of lower priority may end up being omitted from student models, thereby displacing an element of a representation that may be integral in the understanding or purpose the representation itself.

In terms of the representation of the voltaic cell, there are many features which communicate an underlying concept that may be important for the understanding of the diverse chemistry found throughout the voltaic cell. In the case that students potentially regard features with a low enough priority that those features end up being dismissed, there is the possibility that students would experience difficulty in understanding a particular concept. As a result, instructors should thus present the visual representation of the voltaic cell in a manner where students notice the importance of critical features relevant to what instructors want students to learn.

An analysis of Student DC's data comparison also conveyed notions on how viewing a representation may affect a subsequent drawing of said representation. Student DC, despite spending a majority of the time looking at a particular region of a wire, did not draw anything reminiscent of a wire during Phase Three. This result potentially had shown that just because time was spent viewing a particular feature does not mean this feature was understood or noticed. Similarly to Student RL, this may have just been another instance of lower priority being assigned to the wire which was consequently not incorporated in Student DC's model. On the other hand, there was the possibility that the convention which Student DC used to draw the voltaic cell may have caused an inclination to not portray a wire since this shorthand drawing of the voltaic cell conventionally does not include a wire. However, Student DC also incorporated symbolic features presumably representing ionic interactions, another characteristic that is typically not shown in this shorthand portrayal of the voltaic cell. This could suggest that to Student DC, the symbolic representation of the ionic interactions found in the voltaic cell was deemed important enough to incorporate in a drawing at a later period of time, thus making the existence of a hierarchy of priority present within a student's model to be more reasonable. In addition, this inclusion of symbolic features that seem reminiscent of similar symbolic features found within the representation was very surprising considering how little time Student DC spent viewing those corresponding regions on the representation. Thus, this indicated that there exists the possibility where students can incorporate features of a representation in a later drawing even without viewing those features for a period of time. What Student DC had drawn may be due to sufficient prior knowledge that enabled the student to illustrate the symbolic features since little time was spent viewing these features on the representation and there was no input from the interviewer. Student DC's data comparison had shown that there are many ways to which one can view and utilize a representation of the voltaic cell. In this case, it seemed that just because one does not spend time viewing a particular feature does not mean one does not understand or notice that particular feature's representation.

What this revealed was the degree of variation that students can interact with a visual representation such as the voltaic cell. For Students RL and DC, there seemed to be the possibility that viewing a feature may not indicate a noticing and understanding of that feature with regards to the redox reactions and the wire respectively. But for a particular instance of Student DC's data, Student DC's drawing in Phase Three may suggest that not viewing a feature could still lead to a noticing and understanding that feature, at least in the form of a later drawing with regards to the symbolic features found within the anode, salt bridge, and cathode. If instructors intend for students to learn a particular aspect of the voltaic cell by making critical features more noticeable, there still needs to be precautions taken due to how difficult it is to anticipate how students may view a representation and later develop their understanding. It may be more effective to utilize other learning tools such as experiments or online modules in conjunction with visual representations of the voltaic cell in order to better promote a uniform learning event experienced by students.

### Chapter 3.3.3 Assessing Submicroscopic Level Representation

Only 42% of interviewed students included submicroscopic features when cued to think what they would imagine seeing if they had a magnifying glass that hypothetically zoom in as closely as they desired. The submicroscopic features that were drawn by students largely belonged to the following categories determined by analysis of students' post-lived objects: accretion on the cathode, degradation of the anode, ions in solution or ions within the salt bridge, and electrons found within solution or travelling in the wire (Table 9). A checkmark was utilized to denote that the student had incorporated that particular feature in their post-lived object. Submicroscopic features were represented by students as small clumps circles where directionality was represented as the inclusion of arrows. If the drawing were unclear, I would ask the student to clarify by either drawing more or by explaining with words.

**Table 9:** Submicroscopic Features in Post-Lived Object

| | Student LG | Student AS | Student NE | Student QA | Student RL |
|---|---|---|---|---|---|
| Cathode ion particules gather at the cathode to show accretion [submicroscopic] | | ✓ | ✓ | ✓ | |
| Anode ion particules come off the anode to show degradation [submicroscopic] | | ✓ | ✓ | ✓ | |
| Ions in solution [submicroscopic] | ✓ | | | | |
| Ions in salt bridge [submicroscopic] | ✓ | | | | |
| Electrons in solution [submicroscopic] | | | | | ✓ |
| Electron in the wire [submicroscopic] | | | | ✓ | |

25% of the students who did represent submicroscopic features incorporated details on accretion and degradation in their subsequent drawings. One student of the 25% also included a submicroscopic representation of electrons presumably traveling within a wire. The other 17% of students had drawn submicroscopic features relating to ions in solution as well as electrons traveling in solution respectively. It was important to note that the 42% of students who did include submicroscopic features in their post-lived objects did not have any submicroscopic features in their pre-lived objects initially.

During Phase Three, Students QA, AS, and NE incorporated submicroscopic features specifically with molecular interactions conveying concepts of accretion and degradation (Figure 20, Figure 21, & Figure 22). With regards to the accretion of the cathode and degradation of the anode, these three students had used submicroscopic levels of representation that may be interpreted as individual circles either coming off what was identified as the anode or accumulating onto what was identified as the cathode. As shown by the red circles, these three students had also drawn how the anode would get smaller and the cathode would get bigger as their respective processes were to occur. Specifically for Student QA, right below the features related to accretion and degradation, a drawing of electrons moving in a wire was also included in Student QA’s Post-Lived object.

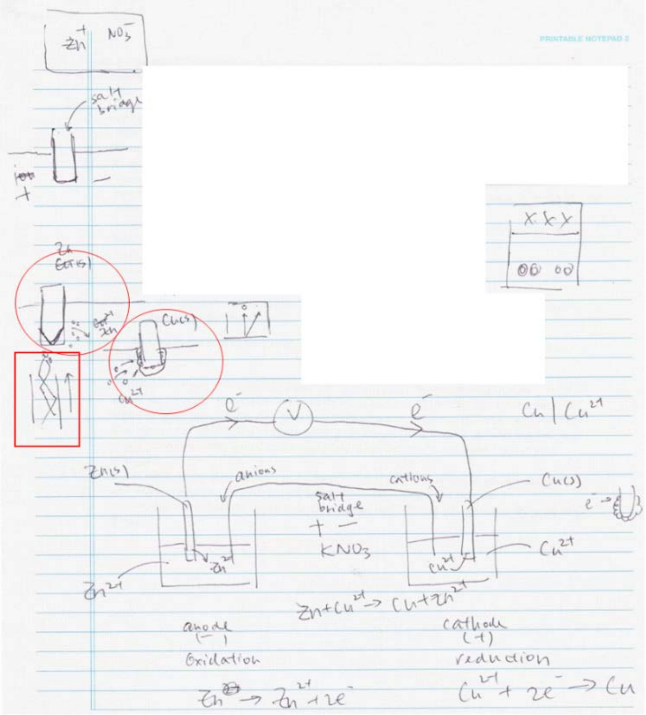


**Figure 20:** Student QA Submicroscopic Features

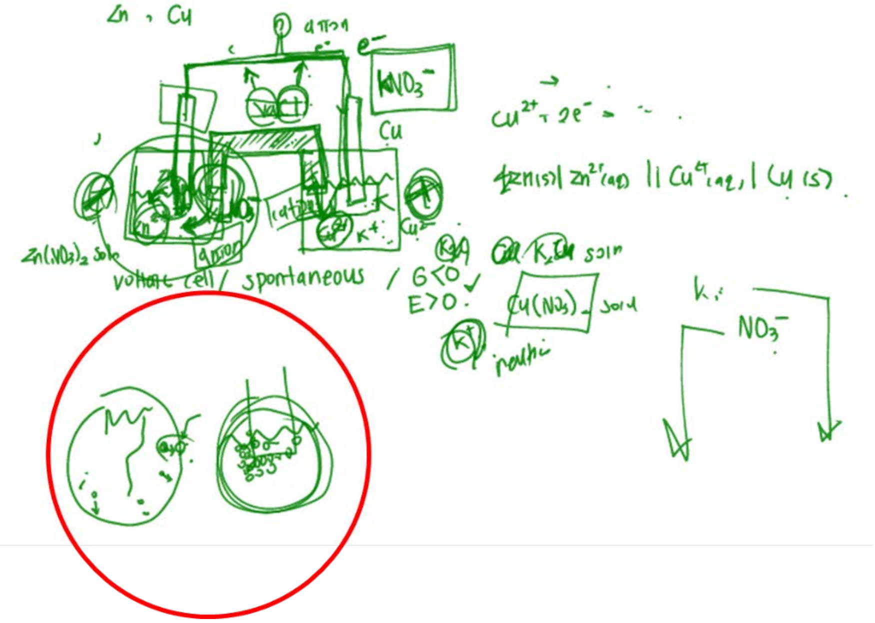


**Figure 21:** Student AS Submicroscopic Features

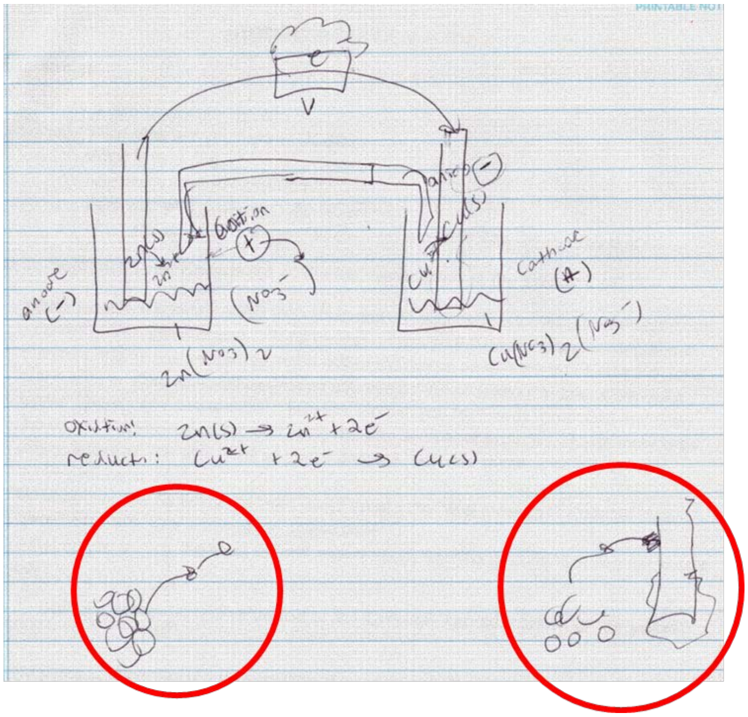


**Figure 22:** Student NE Submicroscopic Features

It was worth noting that although 42% of the interviewed students had drawn the anode getting smaller and 58% of the students had drawn the cathode getting bigger, only half of the 42% had shown the submicroscopic processes relating to the anode while less than half of the 58% had shown similar features for the cathode. These results first indicated that a large percentage (close to half or more than) were most likely able to recall conceptions regarding how the anode and cathode changes over time from their prior knowledge since I the interviewer refrained from stating any of this information.   In addition, students could not have obtained this information from the enacted object of learning since this representation does not explicitly show the loss or gain of mass.  Because even fewer students had represented the submicroscopic features regarding the anode and cathode, this potentially had shown that students may find their macroscopic drawings of the anode and cathode losing and gaining mass respectively to be sufficient even though students were cued to think what they would see when zooming in on the voltaic cell representation. These findings may justify the claim that this particular group of students regarded features of the macroscopic level to be more salient to students' models relative to those of the submicroscopic level despite being orally cued to think at the latter level.

In terms of the other submicroscopic features drawn during Phase Three, only three students had shown other instances besides the anode degradation and cathode accretion. Only Students QA and RL had shown the submicroscopic feature of what was interpreted as electrons outlined by red boxes (Figure 23 & Figure 24).

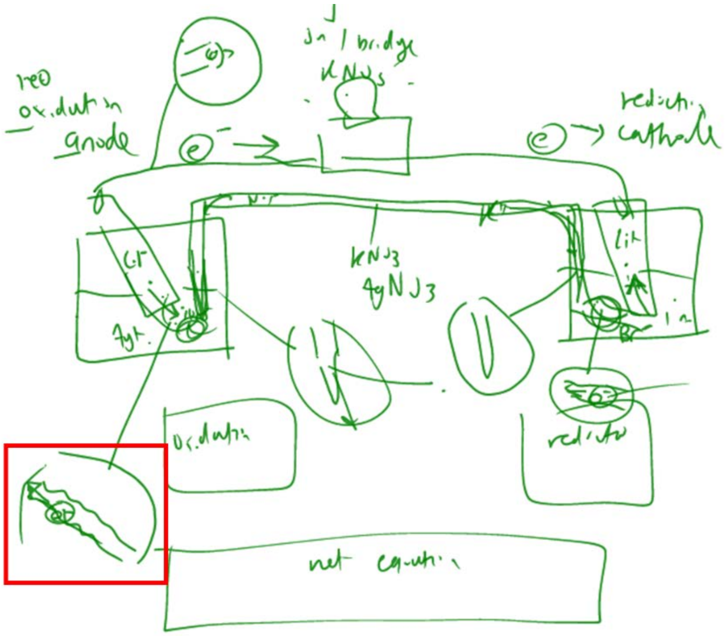


**Figure 23:** Student RL Submicroscopic Features

Student LG was the only student who had drawn the corresponding submicroscopic features, specifically drawing in circles potentially signifying ions within the anode, cathode, and salt bridge as outlined by the red boxes (Figure 20).

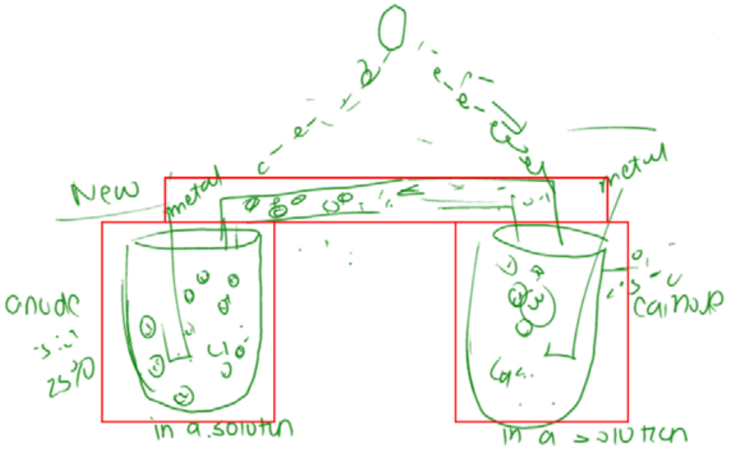


**Figure 24:** Student LG Submicroscopic Features

With the exception of Students LG, RL, and QA, submicroscopic features regarding ionic and electronic interactions were omitted by the rest of the interviewed students within this population. As a result, these results may suggest that these specific students did not include these submicroscopic features in their representations for several reasons. Firstly, due to the potential difficulty in representing submicroscopic processes, students may have not included these in their drawings due to a lack of confidence stemming from insufficient prior knowledge. In the scenario where students do not feel comfortable drawing these submicroscopic features, it would be likely that such features would not be drawn at all. Another reason could be due to these features having less priority in the students' models of the voltaic cell. Similarly to the lack of inclusion of features shown in previous chapters, students not including the submicroscopic features of ionic or electronic interactions could be due to such features having less relevance. This potentially had meant that not having these features in students' drawings may not be reflective of their understanding or lack thereof. All in all, what the results had shown was that even though ionic and electronic interactions is an integral component of the understanding of the voltaic cell, only three student of this population had included the corresponding submicroscopic features. Whether this was likely due to a lack of understanding or priority, instructors should communicate to students the importance of ionic and electronic processes within the voltaic cell and specifically show how they would visually interact accordingly. Otherwise, students may not be viewing the full picture of the chemistry that the voltaic cell entails, providing opportunity for alternative conceptions to develop.

When students were probed to think at the submicroscopic level by pretending they possessed a magnifying glass that can zoom in as closely as they wanted, they exhibited difficulty with the types of answers they would provide. For example, Student SD was asked to describe the purpose of the liquid drawn within the beakers of the student's voltaic cell drawing. The student was able to provide an answer until additional probing necessitated the student to describe the solution in the beakers in the context of ions.

> Interviewer: What's the purpose of the liquid that you drew?
>
> Student SD: To have the reaction with the...with the metal.
>
> Interviewer: Okay. So when you talk about the reaction with the metal...what else is reacting with the metal?

> Student SD: Mmm...the ions in the salt bridge.
> Interviewer: And when they react, how do they react?
>
> Student SD: I don't know.
>
> Interviewer: Okay. Is there any importance on why the ions in the salt bridge would react with the metal ions? Is there any significance to that?
>
> Student SD: Mmm...I don't really know.

In another example, Student NE described what could be possibly observed if there were a zoomed in view of the salt bridge. After Student NE had correctly described the function of the salt bridge, the student had conveyed a degree of confusion when thinking about the individual anions and cations that the salt bridge itself was comprised of.

> Interviewer: What would you imagine seeing in the salt bridge?
>
> Student NE: Hmm...I would see a flow of um...so this cations flowing down here. But like how do they know where to go, that's what I'm wondering too. Like how do this-how do cations know to go here and not there?

Many students such as Student SD or NE had shown that they were unable to tap into, or at times, derive meaning from the solution chemistry present when cued to think at the submicroscopic level. Combining this with how a majority of students did not include submicroscopic features, it may be possible that students have less understanding of submicroscopic features and their associated processes in the voltaic cell when compared to the macroscopic features that were drawn and accurately described by the same group of students. If the understanding of the submicroscopic and macroscopic level of the voltaic cell were not commensurate, students would likely view the voltaic cell with an incomplete or unintended interpretation of the chemistry within. When teaching the voltaic cell representation to students, instructors should highlight both the macroscopic and submicroscopic processes fully, transitioning between the two levels to underscore their interconnectedness as well as their value for an accurate model of the voltaic cell. And the students themselves should not regard the submicroscopic level as a perspective less important than the macroscopic; every level of representation is essential for a complete and scientifically acceptable conception of the voltaic cell.

### Chapter 3.3.4 Omitted Features in Post-Lived Object

Overall, there were features that were present in the representation shown to students during Phase Two which less than half of the population had identified in their post-lived objects. These omitted features included both macroscopic and symbolic levels of representation. The macroscopic features included colors of the solution, degradation of the anode, accretion on the cathode, and a lit light bulb. The symbolic features included ions found in both anode and cathode solutions, denotations symbolizing ions being aqueous, the identification of anode and cathode solution composition, positive and negative symbols normally attribute to the electrodes to denote electron flow, and the net reduction-oxidation equation. In total, there were 13 features that students did not include, 9 of which were symbolic as shown by the yellow highlight. (Table 10).

**Table 10:** Features Omitted in Post-Lived Object

| | |
|---|---|
| **Anode** | The zinc solution color is identified (gray) [macro] |
| | Aqueous solution of the anode is identified as Zn(NO3)2 [symbolic] |
| | Over time, the anode will begin losing mass [macro] |
| | A negative sign is used to label the anode [symbolic] |
| | The subscript [aq] is used to describe the zinc ion [symbolic] |
| | The subscript [aq] is used to describe the nitrate ion [symbolic] |
| **Cathode** | The copper solution color is identified (blue) [macro] |
| | Aqueous solution of the cathode is identified Cu(NO3)2 [symbolic] |
| | A positive sign is used to label the cathode [symbolic] |
| | The subscript [aq] is used to describe the copper ion [symbolic] |
| | The subscript [aq] is used to describe the potassium ion [symbolic] |
| **Light Bulb and Wire** | The light bulb is lit to indicate a flow of electrons [macroscopic] |
| **Misc.** | The net reaction of the redox process is written out [symbolic] |

When viewing Table 5, features that were omitted in student post-lived object but present in the representation shown to students were predominately symbolic that may be associated with particulate chemistry. For example, students not representing the composition of the solutions may have been indicative of their lack of understanding with how these ions interact with one another. However, the symbolic features omitted generally do not clearly show an overall theme that could be solely related to particulate chemistry. Many of these omitted features such as the net reaction or the positive and negative signs to denote direction of electron flow, although may have some connection with particulate chemistry, also share connections with other chemistry concepts that testifies to how multidisciplinary chemistry can be. As a continuation of a similar theme mentioned in prior chapters, many of these omitted features may stem from students not regarding these features with as much importance in their model at that moment of time. Specifically, students may have felt that a net reaction was unnecessary if both the reduction and oxidation reaction were already written out. Students also may have felt the aqueous denotations of ions to not be as important to explicitly illustrate.

In terms of color with respect to the entirety of the voltaic cell representation, students may have omitted any colored feature due to the limitation of the pen itself since the pen provided only black ink. Students were only provided the option of a designated black ink pen for the entire duration of the interview. If students were provided multiple pens of different colors, it would be reasonable to think that students would have potentially treated the assignment of color with a different level of priority. However, students could have circumvented this potential limitation by utilizing the black pen to provide color descriptions adjacent to particular features or describing color with their words instead of illustrating it. After an analysis of student drawings and student transcripts, it was found that the description of color was not acknowledged in a majority of both student drawings and commentary. There were two cases where color was introduced, both of which in very contrasting fashions. For Student SB, color was identified by means of showcasing change in appearance of solution through a progression of time.

> Student SB: And this side I will notice some bubbles, some gas coming out of this solution. Um...besides that...anything...okay. Another thing...another thing I will note is that the color of this solution will become lighter…lighter until there's no color over here.
>
> Interviewer: And why would the solution become lighter?
>
> Student SB: Okay the $CuSO_4$ is blue. And as we...as the Cu goes away...the solution will become like...it's always transparent but it's just losing its color.

Because the enacted object was a static image, the manner in which the student could not only conclude the color would fade over time but also attribute its disappearance to the decreasing number of copper ions in solution was reflective of how robust the student’s prior knowledge of solutions may have been. Student SB could have been cued into thinking about color via the exposure to the enacted object of learning since there was no mentioning of color in the student’s pre-lived object. As a result, the data had shown that visual representations may have played a more varied role in cueing students to attend to certain features. Although the object of learning was meant to be chemistry at the particulate level, students such as Student SB was still able to interpret additional meaning from the voltaic cell representation beyond what was intended.

In a different case, Student TW had mentioned color in the student’s descriptions of the anode and cathode metals. In Student TW’s analysis, color was attributed to both electrodes. Student TW then later described what would happen to each electrode over a period of time.

> Student TW: I think this will become um...this will be oxidationized. [The anode] will lose the color.

> Interviewer: Okay.
>
> Student TW: While this is..this one-this will get I think uh darker.
>
> Interviewer: Darker. And why is it getting darker?
>
> Student TW: Because [the cathode] receive more copper. [The anode] is losing and [the cathode] is receiving.

Student TW had utilized color to convey the notion that as more copper ions would accumulate on the cathode, copper would get darker over time. This type of deduction where more is more (more copper means more color) is a very common heuristic process shown in the literature. Because of this, although the conception was not scientifically accurate, it was reasonable to see how Student TW came to this conclusion.

Shown from the data of Student SB and TW, color was interpreted to potentially be associated with particulate chemistry even though initially color was denoted as a macroscopic feature of the external representation. The reason was that Students SB and TW would associate color with the individual ions, thereby establishing some kind of relationship between the two. In the case of Student TW, it was likely that the student attributed color specifically to individual copper ions. It was interpreted that as copper ions were used for whatever reason, the color of the solution would fade, thereby suggesting that the student had a correct understanding of how copper ions in solution were limited and how they would disappear. Although I cannot make the assumption Student SB understands that the copper ion is becoming copper metal via accretion or why a copper solution is blue, it is nevertheless very likely that Student SB at least has a visual model of a solution where if one were to zoom in would see copper ions contributing to that particular color. Similarly with Student SB, it was likely that Student TW had attributed color to individual ions where losing ions potentially meant losing color and gaining ions potentially meant gaining color. What this suggested was that the Student TW was very likely visualizing the anode and cathode as objects where a zoomed in portion would reveal a collection of individual ions of the same color respectively.

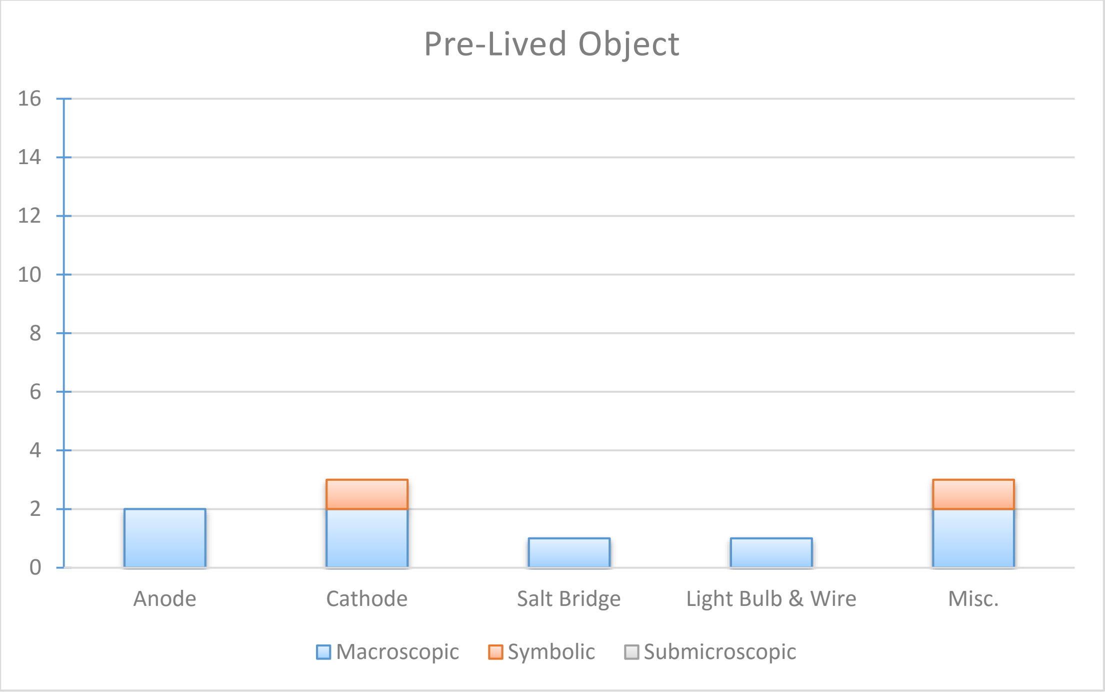
Shown through examples of Student SB and TW, the omitted features of Table 5 can be associated with particulate chemistry even though they may not be explicitly submicroscopic representations in nature. What this suggests is that every part of the voltaic cell representation can potentially instigate conceptions concerning multiple levels of representation even if a feature were portrayed in one particular level. Such a notion is very likely because chemistry essentially is a multi-representational subject. Students are very capable of interpreting the voltaic cell in a variety of unexpected ways and thus require careful guidance from instructors in order to develop a scientific understanding of what they perceive.

# Chapter 4 Conclusions and Implications

Revisiting the research questions outlined in Chapter 2, 31 codes were developed from examining six of the most popular college level general chemistry textbooks available online. These 31 codes were later revised to 51 codes that were used to generate a composite representation of the voltaic cell whose design was to portray the most commonly represented features that general chemistry undergraduate students would potentially be exposed to.

When assessing prior knowledge during Phase One, the results had shown that students' pre-lived objects consisted primarily of macroscopic and symbolic features while lacking in the submicroscopic features (Graph 1).

**Graph 1:** Number of Features that Majority Included in Pre-Lived Object

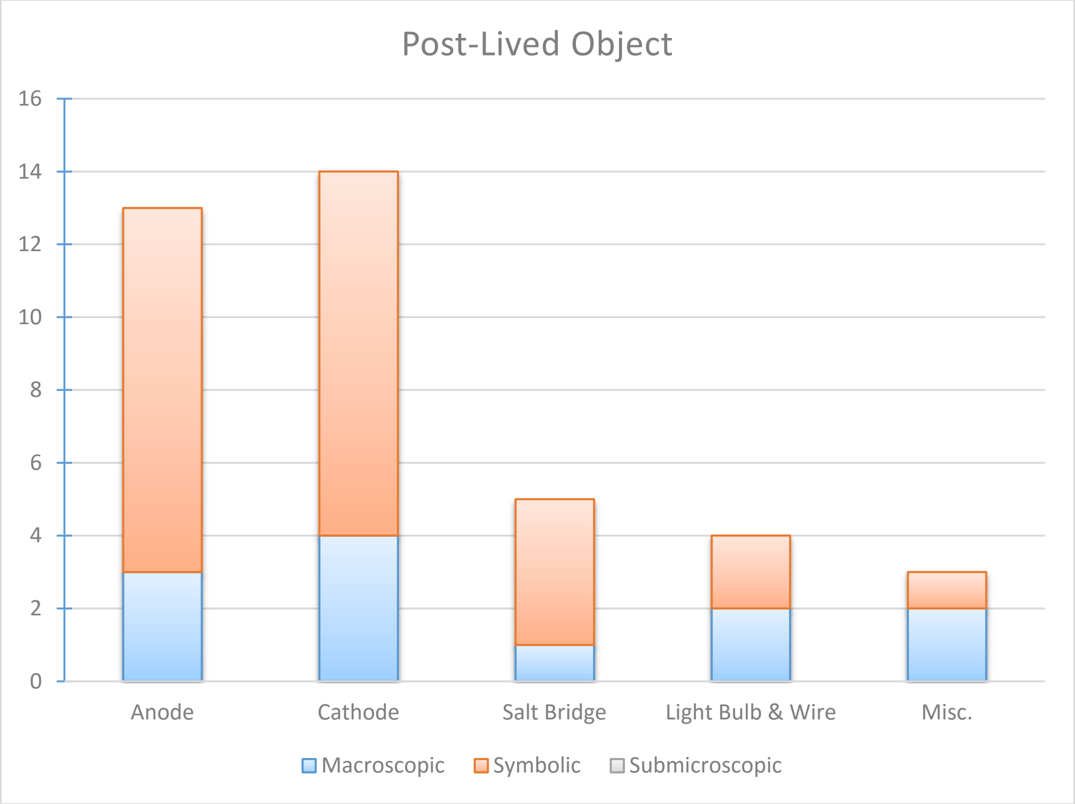


In addition, student transcripts had revealed that there were many alternative conceptions. Every interviewed student demonstrated alternative conceptions in which common themes included ionic and electronic interactions regarding the salt bridge, anode, and cathode.

During Phase Two, three case studies were conducted where the data had shown each of the students viewed the representation in very different manners, attesting to the range of experiences that variation theory aims to capture. The fixation data suggested that there was no consensus in terms of what features students typically spent more time viewing.

After being shown the enacted object of learning in Phase Two, students later produced drawings in Phase Three that included much greater macroscopic and symbolic details, specifically in the anode and cathode regions (Graph 2).

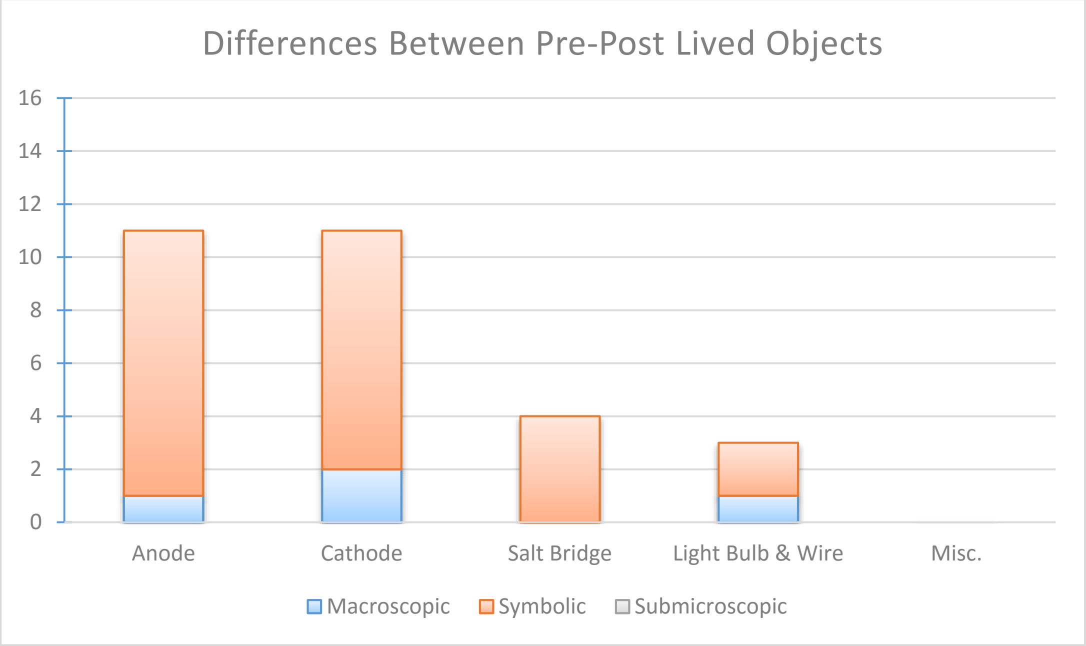
**Graph 2:** Number of Features that Majority Included in Post-Lived Object



Although student drawings now incorporated more symbolic and macroscopic details, there were also emergent alternative conceptions observed during the interviews. These alternative conceptions, initially absent from Phase One, coincided with many of the newly drawn features of Phase Three and dealt largely with the salt bridge and miscellaneous categories in terms of submicroscopic processes of electronic and ionic interactions, similarly to the alternative conceptions of Phase One. Combining the fixation data from the three case studies, it seems that if an individual spends time viewing a particular region for longer periods for time, it is likely that those viewed regions would be incorporated later in a subsequent drawings. However, viewing a particular region for longer periods of time does not suggest that these regions may be noticed or understood. Furthermore, regions where a student may not view at all does not necessarily mean the student will not understand or notice that representational qualities of that particular region. Viewing a representation of the voltaic cell may have led to a reordering of priority of certain features in the student's model at that moment of time, leading to drawings with features the student deems to be more salient for the portrayal of the voltaic cell.

When cued to think at the submicroscopic level by suggesting to students they had a magnifying glass that can zoom in as closely as they desire, only five of students included submicroscopic features. The submicroscopic features that were incorporated dealt with anode degradation, cathode accretion, and presence of ions and electrons. The data suggested that students may not be understanding the particulate chemistry of the voltaic cell due to their omission of submicroscopic features, their associated alternative conceptions that were noted during the interview, and the omission of other features that although symbolic or macroscopic in nature, may still be related to particulate chemistry. Overall, it seemed that students felt that the symbolic level of representation, not the submicroscopic level, was most important to include in their post-lived object (Graph 3).

**Graph 3:** Differences between Pre- and Post-Lived Objects



Such findings align well with the results of other studies: visual representations are effective means in which instructors could enrich student understanding (Nyachwaya & Wood, 2014). In terms of conceptions, participants of this study conveyed difficulty in describing topics such as electronic and ionic interactions that had been previously been affirmed in prior research (Sanger & Greenbowe, 1997; Loh, Subramaniam, & Tan, 2014). The rationale behind why a majority of students did not include the submicroscopic level of representation in their voltaic cell diagrams could be due to several underlying reasons. The first could be due to lack of student familiarity and understanding with the submicroscopic level which has been shown to be a very challenging domain for students to navigate through (Wu & Shah, 2004). The second could be that students do not find the submicroscopic level to be salient in their mental model at that particular moment. This potentially indicates the lack of interconnectedness among the three domains of representation for students or a lack of understanding with respect to the particulate level, a claim that has been supported by prior research as well (Chandrasegaran, Treagust, Mocerino, 2009; Prillman, 2014).

Aligned with those of prior studies, the results of this study support the notion that visual representations can be very effective tools in cueing students to think in a particular manner, deciding what types of information are more important in that particular moment for their model, and enriching their understanding. However, instructors should be careful when choosing a visual representation for their curricula because of the notion that visual representations can be so very easily interpreted by students in a manner contrary to what the instructor may desire. To avoid scenarios of students developing persistent alternative conceptions, instructors must highlight the overlap among the levels of representation if utilizing a visual representation. Research has shown that students experience much greater success in scientific understanding when instructors emphasize the three levels of representation and their corresponding linkages with one another. It has also been shown that when instructors employ this strategy, cognitive load among students is also reduced (Milenković, Segedinac, & Hrin, 2014). Instructors could also refrain from solely relying on visual representations by using other learning tools to enrich student understanding since it can be so difficult to anticipate how a student views and understands a voltaic cell representation as this study's data has reasonably suggested. Therefore, if external representations such as the portrayal of the voltaic cell were utilized in science education, instructors should equally emphasize the three different levels as a coherent message and facilitate the attending of critical features by students in order to promote a scientifically acceptable conception of chemistry.

With respect to the voltaic cell itself, instructors should first identify what they intend for students to learn. After doing so, instructors should portray the voltaic cell representation in a way where the critical features can be noticed and understood by students. From this results of this study, it seemed that students may lack understanding of the submicroscopic processes. As a result, instructors should designate the particulate chemistry of the voltaic cell as the object of learning. To better clarify student confusion or lessen student difficulty, topics that could be more emphasized include how ions of the electrodes and salt bridge interact, how the ions appear in solution, the tracking of electrons in terms of electrons lost or gained by metals, and how electrons and ions interact with one another. Furthermore, instructors should take all of these submicroscopic processes and relate them back to the macroscopic depiction of the voltaic cell, perhaps doing so by zooming into certain regions for more effective clarification on how the submicroscopic and macroscopic levels are interrelated. Teaching the voltaic cell representation without treating the submicroscopic level as importantly as the other levels may result in students not having an understanding of the actual chemistry that takes place within.

# Chapter 5 Assumptions, Limitations, and Future Studies

In terms of the critical features that were not incorporated in the post-lived object, there are two factors that may have acted as limitations for this study. Cognitive load could potentially be a concern as the voltaic cell certainly contains a plethora of information to process, specifically the ionic chemistry in both the anode and cathode solution. Cognitive load is based on the concept of the limitations of working memory in which information passes through a perception filter, enters the working memory space where one becomes consciously aware of said information, and could potentially be meaningfully integrated with prior long term memory to form new knowledge for long term memory safekeeping. However, the capacity for working memory is finite where novices may discern something at a much higher load than experts do (Cranford, Tiettmeyer, Chuprinko, Jordan, & Grove, 2014).

Students lacking adequate prior knowledge may have had a far more inaccessible experience with the exposure to the voltaic cell. This potential issue was mitigated by soliciting students immediately after they have received a foundational instruction on the voltaic cell; however, there may have been variance in terms of what the instructors themselves put forth in terms of their expectations of what students should learn about the voltaic cell. Nevertheless, future studies under the framework of cognitive load theory could provide further insight on how students view the voltaic cell representation and whether cognitive overload was preventing them from incorporating additional features due to overtaxing on their working memory.

In addition, from the results of this study, there is the assumption that students are capable of fully drawing what they want to express or that they are able to accurately describe their conceptions with the language they decide to employ during the interview. Firstly, there can be cases where students were simply unable to draw what they wanted because they lacked the ability to. If a student felt incapable of drawing a particular feature, it would be reasonable to see students neglect illustrating that feature in their drawing. This could potentially explain why students were capable of describing particulate chemistry to a very detailed extent but nevertheless omitted its respective illustration.

Secondly, language may play a crucial role in the sense that students where English was not their first language may experience difficulty in describing certain chemistry phenomenon with regards to the voltaic cell (Svensson, 1997). If a student lacked confidence in the language in which to convey certain thoughts or misused certain words to describe their thought processes, this may lead to different interpretations by the interviewer or students conveying such topics less synonymously with what students actually experience. As a counterpoint to this underlying assumption within this study, one could argue that an individual may not be able to recall all features of an event regardless, and that whatever features are recalled are the most important to that particular individual (Bussey, Orgill, & Crippen, 2013). Such features essentially compose of the mental scaffolding that individuals possess on which further information can be meaningfully constructed upon. Further measures were taken to alleviate the potential issues of language and drawing ability by incorporating multiple pools of data. This study did not rely solely on data from student drawings or interviews but rather a combination of both in conjunction with eye tracking data.

In terms of the eye tracker that was utilized, only three of the students interviewed were able to utilize the eye tracking data, an insufficient number to reach saturation in terms of observations. The eye tracker itself also has potential limitations. When generating areas of interest (such as the anode, cathode, and salt bridge) for fixation layers to be enabled, there has to be as little overlap between each respective region. However, the representation of the voltaic cell is a very complex representation with an amalgamation of multiple features sharing the same space with one another. For example, there is inherent difficulty in determining if a student was looking right above the salt bridge or right below the light bulb and wire. In order to resolve this issue, areas of interest were drawn as broadly as possible without any overlap to best encapsulate the voltaic cell into specific regions. A modified version of the enacted object of learning may be necessary in which each particular area of interest is further spread out to allow for additional space to which the eye tracker could more accurately attribute student eye movement. To further support the direction of this study, one of the goals is to have more participants for the eye tracker in order to not only assess additional examples of how students view the voltaic cell but also to perhaps elucidate the rationale as well. Additional studies in which one explores why students attend to certain features, if students follow a consistent pattern, and whether there is a difference between how experts and novices view the voltaic cell are all potential avenues of research to further shed light on how students meaningfully interpret the representation of the voltaic cell.

A final limitation to this study could have been the way the data was interpreted. It was decided that more than half would constitute as the majority, a metric that was utilized to showcase which features were most commonly represented in student drawings. However, there may not be that much of an appreciable difference between six students which is exactly half compared to seven students which is more than half. In order to remedy this for future implications, one could potentially increase the population size insofar that saturation were to be reached. For qualitative assessments, saturation means that no additional data are being found where the researcher would need to revise codes, meaning that similar instances of results are being observed recursively (Glaser & Strauss, 1967).

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