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Examining Some of Students' Challenges and Use of Algorithmic Problem-Solving Approaches in Electrochemical Titrations

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Redox titration problems are considered difficult for students to learn due to their abstract nature, the myriad amount of representations, and the mathematical competency required to learn and solve. The goal of this research project is to examine challenges students face in learning about redox titration-related problems, approaches they use in learning about electrochemical titration problems, and reliance on algorithmic problem-solving instead of conceptual understanding in solving these problems. The research project took place at the City College of New York, which is an urban, minority serving, and public institution. The research instrument used in this research investigation is a survey comprised of Likert-type and open-ended questions. The number of research participants is n = 184. The data was collected and analyzed and histograms and figures were made based on the data analysis. A single factor ANOVA method was performed on the Likert-type questions which showed evidence against the null hypothesis and that shows a strong relationship between variables. The data indicate that the principal barrier to learning about redox titration related problems is that students' reliance on algorithmic problems solving, rote learning, and mathematical approaches. Students' dependence on rote learning and memorization in problem solving could be attributed to the lack of well-developed understanding of the concepts. The investigation shows that students focus on surface features in learning and this translates to hindrance of knowledge transfer.

Keywords: chemistry education research, redox titration, algorithmic problem-solving

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INTRODUCTION

Students have difficulty understanding and learning about abstract concepts such as electrochemical titrations which would lead to alternative conceptions. Chemistry learning requires understanding and the relationship between the following three components: macroscopic (tangible, visible), microscopic (molecular, atomic, kinetic) and representational (symbols, equations, mathematics) (Johnstone, 1991). This model can be represented as a triangle with each component at each point. Professional chemists are able to blend these three components and move easily between corners. However, students are not required, according to Johnstone (1991), to work within this triangle. Chemists began looking at how students learn, and they began to train students on how to use their existing skills to understand chemistry instead of just omitting difficult chemistry topics. Students must take what they learn and readjust it to suit their existing knowledge and learning methods. To begin understanding how graphical and symbolic representations are used to analyze mathematical reasoning in electrochemical titration, the development and foundation of chemistry learning must be discussed.

Understanding student understanding is essential in chemistry learning research. In a study done to develop the Redox Concept Inventory (ROXCI) as a measure of students' understanding and confidence of redox reactions (Brandriet & Bretz, 2014), many misconceptions were found when students watched an animation of an $AgNO_3$ and Cu reacting. It was found that students were not able to understand that reactants react in a 1:1 ratio, nitrate was the driving force of the reaction and that cations and anions were bonded in aqueous solutions (Rosenthal & Sanger, 2012). This showed that student understanding of the particulate nature of these reactions was not studied in abundance. When analyzing the data from this study it was confirmed that students have alternative conceptions in about redox reactions and are confident in their ideas which suggest their misconceptions are not surface level thus hindering them from addressing these misconceptions.

Understanding molecular processes has always proven difficult in practicing chemistry, particularly because these processes are not directly visible. Therefore, scientists utilized representational methods of communication by organizing information into significant patterns. Scientists use representations to connect underlying chemical concepts to physical substances (Roth & McGinn, 1998). The meaning of a particular representation is often not noticeable without recognizing certain features of the representation. Woolgar (1990) studied scientists examining changes undergone by amorphous alloys under heat. These changes were recorded by a pen-chart recorder where scientists observed the slope and shape of the graphs. The study demonstrates that the meaning of a representation is determined by the features within the representation, in this case the slope, which scientists are expected to recognize (Woolgar, 1990). Other researchers (Campione et al., 1993) have examined the practices of scientists to help design and structure science education. One of these practices is defining knowledge-building communities as people who offer to be studied to produce knowledge products.

As suggested by Roth and McGinn (1998), the use of representations should be the main focus of knowledge-building communities in order to help students understand scientific phenomena. Therefore, one of the key ways to implement graphical and symbolic representation in the classroom is to examine the representational practices of scientists. As demonstrated in earlier studies (Kozma et al., 2000), scientists have a set of representational skills that allow them to utilize and move between different modes of representation to express scientific data/information. These representational skills should be a part of the science curriculum and should be a model for students trying to create representations (Kozma et al., 2000), use representations to explain underlying scientific phenomena, identify symbolic features in a representation, and make predictions based on information obtained from representations.

Alternative conceptions of students in all fields drives the development of new teaching methods and materials. Alternative conceptions provide an inaccurate description of ideas based on one's understanding, which is constructed by their own experience. Student's alternative conceptions in science can lead to more issues with learning as they continue to build their knowledge on the basis of these misunderstandings. To minimize alternative conceptions, multiple representations should be utilized in student learning. As reported by Domin and Bodner (2012), the use of multiple representations helps students in solving problems concerning chemical concepts. When analyzing the use of multiple representations in the lectures of a Fundamentals of Analytical Chemistry course, it was found that in the topic of redox reactions, the most common alternative conceptions is the inconsistency of the understanding between the views of students and scientists, occurred when students were able to balance a chemical equation, but could not draw the molecular diagrams to explain the equations (Pinarbasi, 2007). After introducing multiple representations in the learning process, the percent of student alternative conceptions were reduced. However, alternative conceptions were not resolved when concepts involved microscopic and symbolic appearances. Further activities need to be implemented to change students' misconceptions into facts.

Chemical explanations can be portrayed at three different levels of representation, macroscopic, submicroscopic and symbolic. The macroscopic level includes the observable chemical concepts students experience when doing experiments such as color changes or the formation of new products. To communicate these experiences, symbolic representations are used which include chemical equations, graphs, mechanisms, etc. To explain the experiences of the macroscopic level in terms of the movement of electrons, molecules or atoms, the submicroscopic level of representation is used (Treagust et al., 2003). The use of macroscopic, submicroscopic and symbolic representations simultaneously has been proven to reduce misconceptions when learning chemical concepts (Rodriguez, 2018). Understanding the role and purpose of representations used in teaching to promote mathematical reasoning, enhances how students explain and understand chemical concepts.

Representations have become a crucial aspect of teaching and learning critical thinking. To effectively teach using representations, the right representations must be used. Effective representations capture the important features of a problem instead of representing every aspect. Ineffective representations would hinder the understanding and computation of the student. Learning through representations is dependent on a student's representational ability which is centered around obtaining the ability to build and transform information in a relevant way. Many studies have been done to connect the use of representations to critical thinking and problem solving. In a study, it was found that university students who were able to translate between and manipulate representations scored higher in reasoning ability tests than those whose skills in representations were limited (Stenning at al., 1995).

In addition to improving problem-solving skills, representations have been shown to boost expressiveness in students by getting students and teachers to externalize their ideas. By boosting expressiveness, students are more open to communicate more about their ideas and thinking processes, which results in improved learning and performance. This open communication about the learning process also allows students to track and assess their learning. Modeling problem solving strategies, walking students through drawing representations, and reflecting on the process later, is an important way for teachers to show students how to think and solve problems through utilizing representations. Another important factor in teaching critical thinking through representations is having consistent vocabulary. For example, a student and teacher may discuss a problem and think they are talking about the same thing, however, they have a different definition attached to the vocabulary they are using.

To determine whether the use of computer animations or conceptual change instruction will decrease the number of student misconceptions, Sanger and Greenbowe (2000) conducted a research study to address these issues. The basis for utilizing computer animations during instruction is the dual coding theory which used the idea that forming mental images aids the learning process. Many other researchers have also shown that computer animations aid the learning of chemical processes at a molecular level (Griffiths & Preston, 1992; Williamson & Abraham, 1995). Although students who are proficient in solving other problems using algorithms find it difficult to solve titration related problems (Urbansky & Schock, 2000).

Not only is the utilization of multiple representations and the understanding of their roles important, but the ability to integrate the three levels of representation is also essential. In the context of electrochemistry, the ability to connect the macroscopic, submicroscopic and symbolic levels of representation is required. The reason for students' difficulty with understanding chemistry is often the lack of a third level of representation and therefore the lack of integration between representations (Helsy et al., 2017). Teaching material that uses multiple representations contains a combination of text, real images, videos, and tables to make chemical concepts clearer (Campione et al., 1993). Studies have demonstrated that the use of multimedia in learning has a positive effect of the learning outcomes of students (Ramdhani et al., 2012). In one study, it was reported that teaching materials implemented did have an effect on students' ability to integrate the three levels of representation (Helsy et al., 2017). Integrating the three levels of representations leads to improvement in learning which is due to the fact that teaching materials containing macroscopic, submicroscopic, and symbolic representations, combining text, images, videos and tables, helps students study chemical phenomena (Cheng & Gilbert, 2009). Learning chemistry also involves the establishment of mental associations with the different levels of representation through using different modes of representation.

Conceptual change instruction was used in this study because based on several researchers' data, it was suggested that implementing conceptual change instruction can change student conceptions of chemical processes (Basili & Sanford, 1991; Ebenezer & Gaskell, 1995) and counter student misconceptions in electrochemistry. Therefore, it is crucial for instructors in the field of chemistry to design and implement methods such as conceptual change instruction and animation to encourage the understanding of chemistry.

A student's failure to understand any chemical phenomena can be attributed to many factors. This can occur when students cannot connect new information with preexisting knowledge (Garnett et al., 1990; Nakhleh, 1994), and cannot integrate the different levels of representation as discussed previously. For instance, balancing chemical equations which involves the symbolic level, does not indicate that a student can draw a corresponding diagrammatic form of representation which involves the submicroscopic level.

The adaptation of symbolic and graphical forms is crucial in characterizing the ideas students associate with patterns in a problem. Reasoning using graphical and symbolic forms occurs when students assign mathematical ideas to registrations in a graph. Mathematical reasoning using these forms of representation can be characterized as either static or emergent. Some factors that contribute to the challenge of interpreting graphical forms are the complexity of the graph, including the number of variables and the relationship between variables, a students' mathematical proficiency, and the domain of knowledge required to understand the information being presented. Even when students are presented with the necessary knowledge, they must face the difficult task of blending specific ideas with mathematical reasoning (Rodriguez et al., 2020).

The study of problem solving in chemistry is important because it attempts to bridge the gap between what scientists do when solving problems and what chemistry students are told to do when solving problems (Bodner & Domin, 2002). The initial stages of problem-solving where students attempt to understand the problem involves the construction of a mental representation of the problem (Bodner & Domin, 2002). When examining the success of organic chemistry students, the difference between those successful in organic chemistry and those who are not, is the ability to shift from one mode of representation to another. Unsuccessful students are also not able to break away from verbal representations such as chemical formulas and equations. Successful problem solving is not only affected by the construction of representations, but also the number and kind of representations constructed during the process of problem solving.

Problem solving is a vital part of chemistry courses that can require students to use logical reasoning and decision making to figure out what strategies they need to use. For science classes, problem solving ideally requires conceptual knowledge about the topic at hand as well as procedural (problem solving) knowledge (Surif et al., 2012). This is especially true for more complex problems or composite problems that require multiple steps. However, the problems presented to students in science classes even at the college level are often basic and/or familiar problems that students can solve algorithmically. Surif's and co-authors study (2012) also found that college-level students' conceptual understanding and science process skills were generally weak, especially when it came to a microscopic understanding of the phenomena.

Researchers have demonstrated that presenting teaching materials in varying ways can have an impact on enhancing problem-solving abilities (Sari et al., 2019). Additionally, research in education results suggest that cooperative learning approaches improve mathematical problem solving skills (Demitra & Sarjoko, 2018). For students to be able to blend chemistry and mathematics, they should have the ability to reason using graphical and symbolic representations (Rodriguez et al., 2018). However, if the representation contains too much information or too many symbolic references, the information becomes more abstract and is associated with an increase in student difficulty understanding chemical phenomena (Bain et al., 2018; Becker & Towns, 2012).

METHOD

This project was designed to investigate the challenges that students face in learning about electrochemical titration problems and the approaches they use to solve these problems. The project took place at the City College of New York (CCNY) during the spring and fall semesters of 2020 and spring of 2021. The City College of New York is an urban minority serving public college with a commuter student body. All participants in this project had successfully completed one year of General Chemistry courses and were enrolled in upper level courses at the time they were surveyed. We created a survey made up of both Likert-type and open-ended questions in order to gather data about student conceptions and practices. The survey was reviewed by two experts in assessment who verified that the questions adequately and objectively evaluated student understanding of electrochemical titrations. A test-retest reliability analysis produced a reliability coefficient of 0.80 for our survey. The survey comprised of six Likert-scale and six open-ended questions. The survey was administered to, and collected from 184 participants with approval from the CCNY Internal Review Board (IRB).

The Likert-type questions were on a five-point scale using numerical values as follow: Strongly disagree (1), disagree (2), neutral (3), agree (4), and strongly agree (5). We performed a single factor ANOVA on our Likert-type questions in order to understand the variability of the student responses to them. Insufficient variability in student responses to a question would indicate that it either did not accurately reflect student experience or that student experience of the issue at hand was too uniform to be informative. The average numerical value of student responses for each question were calculated and displayed in histograms.

For three of the open-ended questions, we used a rubric to convert the respondents' answers into numerical values ranging from 1 to 5. As in the Likert-type questions these values were averaged and displayed in histograms. Responses to two of these questions were diverse enough that a pie chart was used to display the various student responses.

We should note that our research results and conclusions are based on data collected from the City College of New York which is a minority serving institution in an urban commuter setting. Our student population is rich with diversity and we did not account for that our data analysis. Also, the courses are taught by traditional lecture format. A similar research study with data collected from several different institutions with different teaching and learning approaches could provide valuable insights and build on the findings of this study. Additionally, this study investigated students' challenges and alternative conceptions about electrochemical titrations based on data obtained from a survey. The study can be made more comprehensive by interviewing students and asking probing questions about their alternative conceptions and challenges in learning about the concepts studied.

Guiding Research Questions

1. What difficulties do students experience in understanding electrochemical titration problems?

2. What approaches do students use to solve redox titration-related problems?

3. Do students rely on algorithmic problem-solving instead of conceptual understanding in solving redox titration problems?

FINDINGS AND DISCUSSION

A single factor ANOVA method was performed on the Likert-type questions section of the questionnaire. P was calculated and found to be $P<0.05$ which indicates evidence against the null hypothesis and that shows a strong relationship between variables. Furthermore, the data analysis shows that the mean-square between groups is 8.631 which is significantly larger than the mean-square within groups of 0.782. The ratio between groups-mean square and within-groups mean square is 11.03 which is large enough to reject the null hypothesis with confidence.

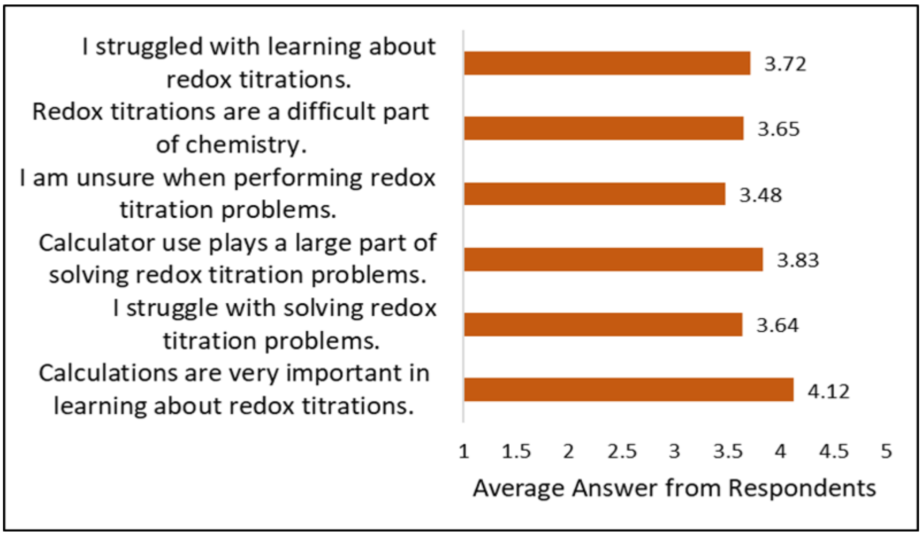

Figure 1
Average responses of students to Likert-type questions in our survey. The range of answers was: strongly disagree (1), disagree (2), neutral (3), agree (4), and strongly agree (5).

Likert-type questions and their averages are presented in Figure 1. The figure shows that students' perceptions about redox titration problems is that they struggle learning about and solving these difficult concepts and that they consider them to be a difficult part of chemistry. This is supported by research in science education that reveal instructors and their students regard electrochemistry as one of the most difficult concepts to learn in chemistry (Lin et al., 2002).

The students also agree that they are unsure about how to solve redox titration problems but they underscore the importance of calculators to solving redox titrations problems. Finally, the students agree to the importance of the role of calculators in solving redox titration problems. This is consistent with research in science education reports that students rely on algorithmic problem solving instead of development of conceptual understanding, which allows them to solve problems on examinations in traditional lecture and assessment format, and this can negatively impact their learning and conceptual understanding (Sanger & GreenBowe, 2000).

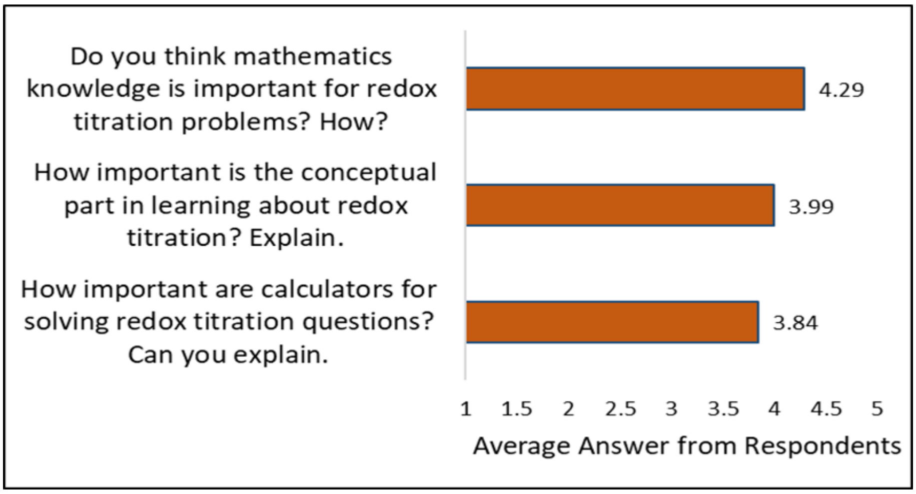

Figure 2
Open-ended questions

Three of our open-ended questions (Fig. 2) were developed to evoke student feelings about the importance on mathematics and conceptual understanding in solving redox titration problems. These questions were evaluated using a rubric that scaled responses from 1 to 5 with an increasing score positively correlating with agreement to the premise of the question. Again, the students place emphasis on the significance of mathematical knowledge in learning and solving redox titration problems and they consider the contribution of calculators to successful solutions to redox problems. Students' abilities to perform algorithmic problem solving, algebraic manipulations, and symbolic mathematical representations does not translate to meaningful learning, conceptual understanding, or the ability to transfer knowledge to new concepts (Mason et al., 1997).

The students' perceptions are that they need to develop conceptual understanding to solve redox titration problems. For students to develop conceptual understanding of electrochemistry, they need to have an understanding of the topic of electricity from physics, and the structure, properties, and particulate nature of matter from chemistry, and the mathematical knowledge required for meaningful learning. Electrochemistry teaching and learning poses challenges to students because redox reactions and processes involve conceptual and procedural components (De Jong & Treagust). The procedural component refers to the calculation part and the conceptual part is concerned with the understanding of the electron flow, ions movement, cathode and anode identification, balancing redox reactions, charges, and oxidation numbers. Constructivists and cognitive learning theories underscore the importance of learning and construction of knowledge based on prior knowledge (Kwan & Wong, 2015).

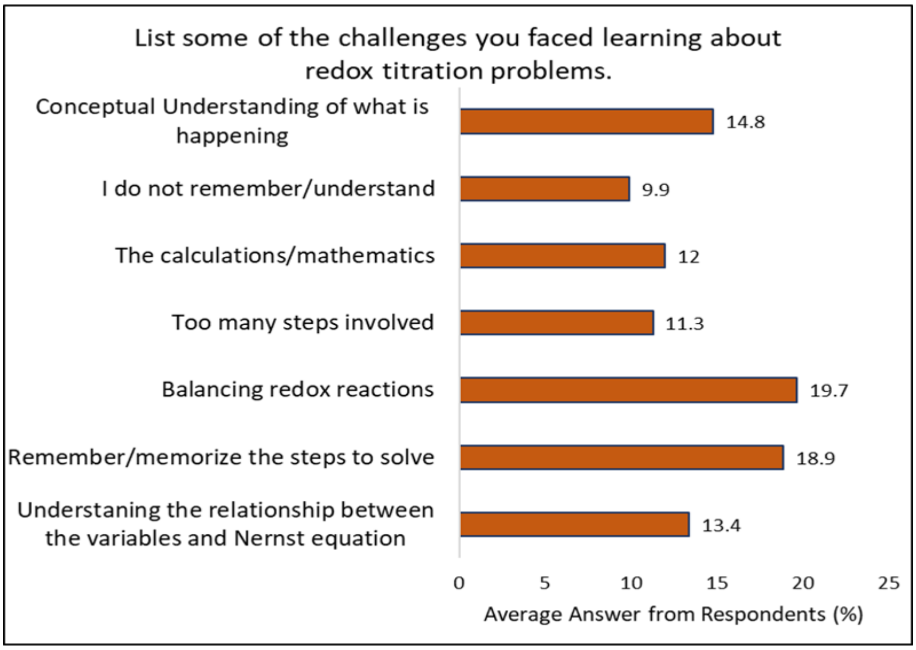

Figure 3
List some of the challenges they faced in learning about redox titration problems

Student responses to open ended questions about the challenges they faced in learning about redox titration problems were broken down into seven principle categories. The distribution of these responses was fairly uniform, but remembering formulas and the steps to solve and balancing redox reactions were dominant responses.

Figure 3 is a depiction of some of the challenges that students faced in learning about redox titrations problems. The data show that 14.8% of students struggle developing conceptual understanding of the topic and that 13.4% of students reveal that they lack an understanding of the relationship between the variables and Nernst equation. Researchers have identified several conceptual difficulties and alternative conceptions about electrochemistry concepts which include galvanic, electrolytic cells, and electrode potential (Amponsah & Ochonogor, 2018; Amponsah et al., 2018). Lack of development of an understanding of the three levels of representations and their relationship leads to difficulties in learning about electrochemistry (Phillip et al., 2014). Students have to understand what is taking place at the microscopic level such as the movement of ions and electrons and relating it the symbolic level in the form of formulas and mathematics.

Figure 3 also shows that 12% of students consider the calculations and mathematics as the parts that cause them the most difficulties. Students find difficulties in learning chemistry due to its abstract nature, relating the three representations of microscopic, macroscopic, and symbolic, and interpreting the mathematical component of the subject matter (Hadfield & Wieman, 2010). Furthermore, for students to learn and problem solve redox related problems, conceptual reasoning should be emphasized in quantitative problem solving at the initial quantitative analysis (determining the relevant mathematical equations) and at the final answer of quantitative analysis (checking for plausibility of results and physical meaning) (Redish & Smith, 2008).

The students revealed that they face challenges remembering the steps to solve (18.9%) and that there are too many steps involved in the problem solving process (11.3%). One explanation is that electrochemistry which is a dynamic process is presented in textbooks as a static process which causes difficulties in relating different representations to one another and there is a need to allow for visualization of that is taking place during the electrochemical processes (Ploetzner et al., 2009).

About 10% of participating students report that they struggle solving redox titrations problems because of the lack of understanding. Electrochemistry concepts have been determined to be abstract in nature and thus challenging for students to comprehend (Rogers et al., 2000). Research in science education have reported that students face difficulties in learning about the abstract nature of chemical processes in electrochemistry in particular at the submicroscopic and symbolic levels (Lin at al., 2002). Additionally, science education research reports that electrochemistry concepts and problems have been found to cause the most difficulties and ambiguities for students to learning due to their abstract nature and their representations at the symbolic level in the absence of relationship to submicroscopic and macroscopic representations and their dynamic processes (Ochonogo, 2011).

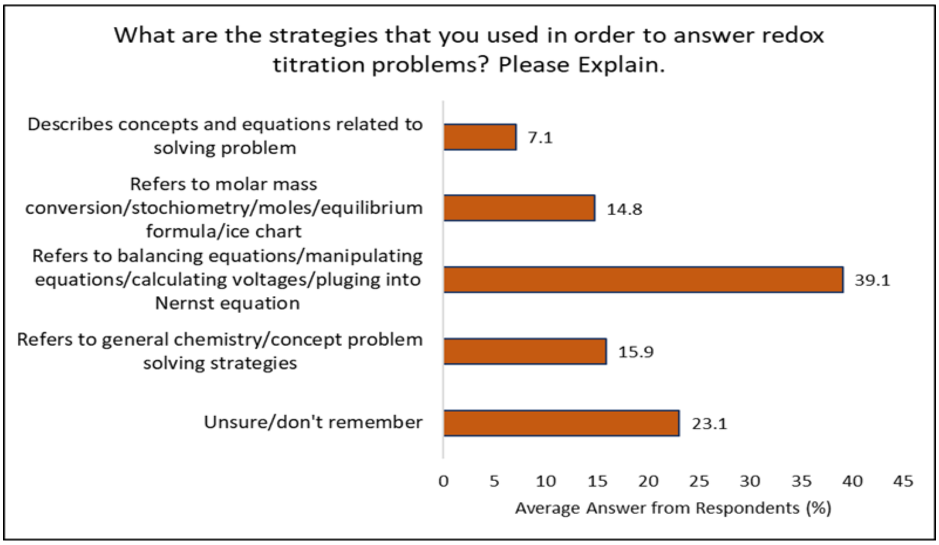

Figure 4
The strategies they used to solve redox titration problems

Student responses to open-ended questions about the strategies they used to solve redox titration problems fell into five basic categories. Balancing equations and mathematical calculations were the dominant responses.

Students' strategies to solving redox titration problems are presented in Figure 4 and these include balancing equations, manipulation variables, and calculations (39.1%). Student reliance on algorithmic problem solving but lack of conceptual understanding has been documented by researchers in science education (Fach et al., 2007). One possible explanation for students' dependence on algorithms in problem solving is the lack of understanding of the basic concepts which hinders their ability to transfer this knowledge and translate it into successful problem solving strategy (Bodner & Herron, 2002). Additionally, it has been shown that often students can use memorized steps in a calculation or an algorithm to solve problems in their chemistry class even with a weak understanding of the concepts (Surif et al., 2012).

The ability to solve science problems quantitatively is essential to successful science learning (Reif, 2008). One of the major challenges students face in learning about electrochemistry is the requirement of higher order thinking skills and the ability to relate the three levels of representations: symbolic, microscopic, and macroscopic (Lee & Osman, 2014). It is important to note that conceptual knowledge and procedural skills are both required to be a skilled problem solver in the sciences. Ideally, our students are challenged with problems that require them to access this knowledge and skill set as opposed to memorizing steps and applying them to a new set of values.

Figure 4 shows that a significant number of participants (23.1%) are unsure or do not remember how to solve. Remembering steps might have to do with the fact that students rely on memorization and rote learning instead of development of conceptual understanding and the different representations involved and the dynamic processes that take place during a redox titration. This is supported by the findings of Heyworth (1998) that students of all achievement levels "tend to rely mainly on algorithms" to solve chemistry problems rather than their knowledge base or conceptual understanding (Surif et al., 2012).

The figure shows that 14.8% refer to molar mass, stoichiometry, ice charts, and equilibrium and another 15.9% of students refer to general chemistry concepts and problem solving strategies. This could be explained as an attempt by students to carry out a successful transfer of knowledge. The students are familiar with neutralization titration problems but could have relied on mathematical and algorithmic problem-solving approaches to perform well on traditional examinations. This leads to a lack of development of conceptual understanding or meaningful learning of the concepts and therefore students are unable to transfer knowledge to new situations as in redox titration. This is consistent with research in science education that reports meaningful learning of chemistry concepts and problem solving should promote students' abilities to transfer knowledge and the application of what is learned into new unfamiliar situations (Bransford & Schwartz, 1999).

Additionally, successful transfer of knowledge depends on whether students develop conceptual understanding, rely on memorization, nurture their metacognition, and promote their motivation (Johnson et al., 2011). Instructors need to change the way they teach their students and must address students' inabilities to effectively transfer knowledge to new concepts or problems (Brophy et al., 2008). The participants in our study focused on surface features in learning and this translated to inabilities to transfer knowledge and problem solving ability. Good problem solvers who are capable of transfer of knowledge into new situations recall underlying conceptual structures from previous problems as opposed to relying on surface features (Sutton, 2003).

CONCLUSION

The data presented in this paper show that students face difficulties learning about and solving problems related to redox titrations. Also, the participants underscore the importance of and the significance of the role of calculators in solving redox titrations problems. Additionally, students emphasize the importance of mathematical knowledge in learning and solving redox titration problems and they consider the positive contributions of calculators to successful solutions to redox problems. We should also note that students perceive the need to develop conceptual understanding of chemistry topics to solve redox titration problems.

The data reveal that students struggle developing conceptual understanding of the topic and that they lack an understanding of the relationship between the variables and Nernst equation. It is important that students understand what is taking place at the microscopic level such as the movement of ions and electrons and relating it the symbolic level in the form of formulas and mathematics. Students consider the calculations and mathematics as the parts that cause them the most difficulties in learning about redox titrations. Students also report that they face challenges recalling the different steps and that there are too many steps in the solution of the problems. Students might rely on memorization of steps in algorithmic problem solving due to lack of well-developed conceptual understanding of the concepts. Furthermore, students report that they struggle solving redox titrations problems because of the lack of understanding.

Students approach solving electrochemical titration problems by relying on balancing equations, manipulating variables, and calculations. This algorithmic and formulaic approach to problem solving demonstrates weak conceptual understanding and can hinder transfer of knowledge and impede problem-solving ability. It is important to note that conceptual knowledge and procedural skills are both required to be a skilled problem solver in the sciences. Ideally, our students are challenged with problems that require them to access this knowledge and skill set as opposed to memorizing steps and applying them to a new set of values.

The research investigation reveals that students tried to carry out a successful transfer of knowledge. The students are familiar with neutralization titration problems but could have relied on mathematical and algorithmic problem-solving approaches to perform well on traditional examinations. The participants in our study focused on surface features in learning and this translated to inabilities to transfer knowledge and problem solving ability. The lack of well-developed conceptual understanding or meaningful learning of the concepts hinders students' abilities to transfer knowledge to new situation as in redox titration. There is currently a gap between the problem-solving skills of scientists and the problem-solving skills of students. Therefore, the construction and integration of the various levels of representations must be implemented effectively in teaching chemistry to encourage the development of important problem-solving skills.

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