

Prospective teachers' conceptual understanding of electrochemistry: Galvanic and electrolytic cells

*Ali Rıza Özkaya^a, Musa Üce^b and Musa Şahin^b

^aChemistry Department, Faculty of Science and Letters, Marmara University, 81040 Kadıköy, İstanbul, Turkey,
e-mail: aliozkaya@marmara.edu.tr

^bDepartment of Science and Mathematics Education, Atatürk Faculty of Education, Marmara University, 81040 Kadıköy, İstanbul, Turkey,
e-mail: musauce@marmara.edu.tr ; musasahin@marmara.edu.tr

This study investigated prospective chemistry teachers' conceptual difficulties in understanding basic aspects of electrochemistry related to galvanic and electrolytic cells. It was conducted with ninety-two prospective teachers who were students in the final year class at Marmara University, Atatürk Faculty of Education and had received both classroom and laboratory instruction on electrochemistry for about three and a half months (3 hours per week for both classroom and laboratory instruction). Fifteen volunteers from among the group were first interviewed for about 40-45 minutes. After the interviews, a test of 27 multiple-choice questions, consisting of assertion-reason statements and a set of alternative answers, was administered to all subjects. This study was able to identify new electrochemical misconceptions as well as some of those previously reported. The results show that students from different countries and different levels of electrochemistry study have similar difficulties and suggest that concepts are presented to them poorly. It also discusses some of the possible origins of these misconceptions.

Introduction

There have been a large number of studies that reported students' understanding of various science topics. Studies in this area included students as well as teachers. More studies have been conducted with students at secondary schools and universities rather than with teachers and prospective teachers, but there have been a number concerning conceptions of teachers and prospective teachers. Bradley and Mosimege¹ investigated misconceptions of South African prospective teachers about acids and bases through a twenty-item questionnaire divided into twelve multiple-choice items and eight discussion items. They reported that the prospective teachers' performance in these was disappointing. Kokkotas et al.² noted that Greek prospective teachers share a number of misconceptions with pupils. Haidar³ investigated the extent of Yemen prospective teachers' understanding of certain fundamental theoretical concepts such as atoms and mass, the mole, atomic mass, and balancing chemical equations. He reported that their understanding of most of these concepts ranged from a partial understanding with specific misconceptions to no understanding and that their knowledge about the concepts was fragmented and not correlated. The results of his study also showed that they only memorized the concepts without meaningful understanding. Quilezparado and Solazportoles⁴ developed a written

test to diagnose both students' and teachers' alternative conceptions about chemical equilibrium. They stated that misconceptions emerged through:

- misapplication and misunderstanding of Le Chatelier's principle;
- the use of rote-learning recall and algorithmic procedures;
- incorrect control of the variables;
- limited use of the chemical equilibrium law;
- a lack of mastery of the principles of chemical equilibrium and difficulty in applying such principles to new situations.

Pardhan and Bano⁵ reported on a qualitative research study carried out on science teachers' alternative conceptions about electricity. They also discussed the nature and origin of the alternative conceptions of teachers. Trumper et al.⁶ discussed the similarities and differences for Israeli and Argentinian prospective teachers' conceptions about energy. They noted that there was a serious discrepancy between both Israeli and Argentinian student teachers' understanding of energy and the accepted scientific concepts. They concluded that the students' understanding of energy needs to be improved. Chang⁷ administered an open-ended, written test to 364 students in a teacher training college and interviewed a representative selection of students in a semi-structured manner to discover their conceptions about evaporation, condensation, and boiling. Examining the students' ideas

carefully, the researcher concluded that learning difficulties regarding these concepts could be a result of poor understanding of what water vapour is. A study reported by Yip⁸ revealed that novice biology teachers held a number of conceptual errors about various biology concepts, which were also prevalent among secondary school students. Specific teaching strategies were suggested to prevent the propagation of these misconceptions to students. These studies confirm that students at all levels, and even science teachers, hold misconceptions as well as conceptual and propositional knowledge that is inconsistent with or different from the scientific consensus, and are unable to explain adequately observable scientific phenomena (Nurrenbern,⁹ de Jong et al.,¹⁰ Quilezparado and Solazportolez⁴).

Science educators are paying increasing attention to students' conceptual difficulties in the field of electrochemistry. Several researchers have reported that students find the topic difficult (Bojczuk;¹¹ Finley et al.;¹² Butts and Smith;¹³ de Jong¹⁴). Allsop and George¹⁵ reported that students have difficulty using standard reduction potentials to predict the direction of chemical reactions and were unable to produce an acceptable diagram of an electrochemical cell. Birss and Truax¹⁶ noted that students who learn electrochemistry from most high school and first-year university textbooks are likely to experience confusion on this subject. They also discussed the most important problems students are likely to encounter. Garnett et al.¹⁷ discussed students' understanding of electrochemistry, with the aim of improving science curricula. In subsequent articles, Garnett and Treagust^{18, 19} identified common student misconceptions about oxidation-reduction reactions, electric circuits and galvanic and electrolytic cells by using student interviews, and discussed some probable origins of these misconceptions. Ogude and Bradley^{20, 21} investigated pre-college and college students' difficulties regarding the qualitative interpretation of the macroscopic processes that take place in operating electrochemical cells. They stated that although many students can solve quantitative electrochemical problems in exams, few are able to answer qualitative questions that require a deeper conceptual knowledge of electrochemistry. Sanger and Greenbowe^{22, 23} applied Garnett and Treagust's interviews¹⁹ on galvanic and electrolytic cells to their own subjects and extended them by addressing student misconceptions about concentration cells. Subsequently, they analyzed college chemistry textbooks as sources of misconceptions and errors in electrochemistry (Sanger and Greenbowe²⁴). Huddle et al.²⁵ reported a concrete model to correct known misconceptions in electrochemistry. Recently, Thompson and Craig²⁶ investigated the concept of electrochemical equilibrium in relation

to thermodynamic functions with the aim of providing pedagogical support for undergraduate analytical chemistry students. The subjects of these studies were either high school or college students.

We could not find a research report in literature on the alternative electrochemistry conceptions of prospective teachers. There are only a few reports on the electrical concepts of science teachers (Webb;²⁷ Pardhan and Bano⁵). Furthermore, previous studies¹⁵⁻²⁵ do not investigate electrochemical concepts such as chemical equilibrium, electrochemical equilibrium, and the instrumental requirements for the measurement of cell potential or electromotive force (emf). Therefore, we embarked on a study designed to identify previously reported and new electrochemical misconceptions of prospective chemistry teachers, considering previously uninvestigated concepts.

An earlier paper (Özkaya²⁸), concentrated on identifying prospective teachers' new misconceptions, taking into account previously uninvestigated concepts, but reported on only some of these. This paper focuses on misconceptions that are common with those of students from different countries and different levels of electrochemistry. It also discusses new misconceptions not reported in the earlier paper.

The purpose

This study investigated prospective chemistry teachers' conceptual difficulties in understanding basic aspects of electrochemistry related to galvanic and electrolytic cells after they had received a course of electrochemistry instruction. In the study we attempted to answer three questions.

- Which of the common misconceptions about electrochemistry reported by Garnett and Treagust,^{18, 19} and Sanger and Greenbowe^{22, 23} are held by our student teachers?
- Do they hold new misconceptions not previously reported?
- What are the likely sources of their misconceptions?

The sample

The sample consisted of ninety-two prospective teachers who were students in the final year class at Marmara University, Atatürk Faculty of Education. The study was conducted after they had received both classroom and laboratory instruction on electrochemistry for about three and a half months (2 hours per week for classroom and 3 hours per week for laboratory instruction). The electrochemistry laboratory and classroom instruction covered the following topics: metallic

and electrolytic conductance, conductimetric titration, systematic investigation of cells, thermodynamic functions of galvanic cells, potentiometric titration, Faraday Laws, electrolysis and polarization, electrochemical corrosion, and some electroanalytical methods (amperometry, polarography and cyclic voltammetry). The students were instructed by traditional lecture and quantitative problem-solving approaches.

Methodology

Fifteen volunteers from among the ninety-two were first interviewed for about 40-45 minutes using the protocol of Garnett and Treagust^{18, 19} to which the following questions were added:

- How is the emf of a cell measured? Is it possible to use an ordinary voltmeter to measure the emf of a cell precisely?
- Under what conditions is an electrochemical equilibrium established in a galvanic cell?
- Under what conditions is a chemical equilibrium established between the species involving in the cell reaction in a galvanic cell?
- What happens when a metal is immersed into an electrolyte solution involving its ions?

The interview subjects were selected on the basis of their performance in the electrochemistry course, with five students from the top third of the class, five from the middle third, and five from the bottom third. Before the interviews, the students wrote their responses on the question sheets. During each individual interview, the conversation was recorded. The responses were analyzed to identify the students' conceptual difficulties.

After the interviews, a test of 27 multiple-choice

questions, consisting of assertion-reason statements and a set of alternative answers, was administered to all subjects. The test items did not cover all the classroom and laboratory topics, only the basic concepts of galvanic and electrolytic cells. Some of the assertion-reason statements were based on students' alternative ideas reported previously in literature.^{18, 19, 22} This allowed us to test for previously reported misconceptions. Other assertion-reason statements were based on either the subjects' scientifically incorrect responses during the interviews or on concepts not previously investigated. This made possible the identification of misconceptions not previously reported.

Results and discussion

The students' misconceptions identified in this study are given in the Appendix. These misconceptions were classified into five areas:

- Electrode potentials and cell emf
- Identifying the cathode and anode
- Metallic and electrolytic conduction
- Chemical and electrochemical equilibrium
- Predicting electrode and cell reactions

The results from the analysis of test questions examining each area are discussed below.

Electrode potentials and cell emf

Some questions in the twenty-seven-item test (Questions 1-7) were designed to test the students' understanding of electrode potentials and cell emf. Question 6 and the subjects' responses to it are shown in Table 1 as an example. Of the fifteen subjects interviewed, four stated that standard half-cell potentials can be used to predict the spontaneity of the reaction involving in the half-cells, since some standard half-cell potentials are

Table 1

Question 6

| Assertion | | | <i>because</i> | Reason | | |
|--|---------------------------------|------------------------------|----------------|--------|--|--|
| Standard half-cell potentials can be used to predict the spontaneity of the reactions involving the half-cells | | | | | Some standard half-cell potentials are positive while the others are negative in value | |
| Answers to question 6 | | | | | | |
| Alternative | Statement 1 <i>Assertion</i> | Statement 2 <i>Reason</i> | Alternative | n | % | |
| a* | True | True | a | 42 | 45.7 | |
| b* | True | True | b | 30 | 32.6 | |
| c | True | False | c | 0 | 0 | |
| d | False | True | d** | 18 | 19.6 | |
| e | False | False | e | 2 | 2.1 | |

*The difference between alternatives *a* and *b* was explained before the test. In both cases statements 1 and 2 are both true, but in *a* the reason statement correctly explains the assertion and in *b* it does not.

**Correct answer

positive while the others are negative in value. Therefore, question 6 with appropriate assertion-reason statements was designed on the basis of this scientifically incorrect idea (Table 1). The results from the analysis of question 6 were consistent with the subjects' responses during the interviews. A significant proportion of the subjects marked either 'a' or 'b'; they held misconception 1 (Appendix). Of the seventy-two subjects, who marked 'a' or 'b', forty-two thought that the reason statement "*Some standard half-cell potentials are positive while the others are negative in value*" correctly explains the assertion statement "*Standard half-cell potentials can be used to predict the spontaneity of the reactions involving in the half-cells*". Therefore, this alternative idea can be expressed as a new misconception (2, Appendix).

In response to a question, nearly all students correctly stated that it is not possible to measure a half-cell potential without using another half-cell; they did not hold the previously reported^{19, 22} misconception: "*A standard half-cell is not necessary*". However, in response to another question, half of the subjects believed that the electrode potential is equal to the electrochemical potential difference between the metal and electrolyte in the half-cell, since both can be expressed in volts. This alternative idea was regarded as misconception 3 (Appendix). These subjects were unaware that the electrochemical potential is composed of electrical potential and chemical potential, and that when a metal is immersed into the electrolyte involving its ions, the electrochemical potentials of two phases become equal in a very short time i.e., an electrochemical equilibrium is established between the metal and its ions in the electrolyte.

In the interviews, of the fifteen subjects responding to the question "*Why does $H_2(1\text{ atm})/H^+(1M)$ standard half-cell have an E^0 value of 0.00 V?*" four could not offer a reason. Eleven correctly stated that it was arbitrarily set at 0.00 V. However, four of those eleven suggested that there should be a relationship between the value of zero and chemistry of H^+ and H_2 , and proposed a variety of reasons why the standard hydrogen electrode potential is set at 0.00 V. The most popular reason was the statement "*Hydrogen is in the middle of the activity series for metals*". On the basis of their responses, a question was designed with appropriate assertion-reason statements. The assertion statement was a scientifically incorrect idea: "*The value of zero for the standard reduction potential of the $H_2(1\text{ atm})/H^+(1M)$ standard half-cell is based on the chemistry of H^+ and H_2* ". The results of the test were in accordance with the responses in the interviews; forty-two subjects (46%) thought the statement was true. These subjects held misconception 4 (Appendix). On the other hand, twenty-five of forty-two subjects thought that the reason statement, "*Hydrogen is in the middle of the activity series for metals*", correctly explains the assertion statement. This alternative idea is regarded as a new misconception (5, Appendix).

Identifying the cathode and anode

During the interviews, the students showed widespread uncertainty about the reactions that occur at the electrodes and the assignment of electrodes as (+) and (-) in galvanic and electrolytic cells. Five questions were designed to probe their understanding in this area. Question 9 and the subjects' responses to it are shown in Table 2. The assertion statement "*In galvanic cells, oxidation occurs at the anode and reduction at the cathode,*

Table 2

Question 9

| Assertion | | | because | Reason | | |
|---|---------------------------------|------------------------------|-------------|---|------------------------------|---|
| In galvanic cells, oxidation occurs at the anode and reduction at the cathode, while in electrolytic cells oxidation occurs at the cathode and reduction at the anode | | | | In galvanic cells, the anode is labelled as (-) and the cathode as (+), while in electrolytic cells the anode is labeled as (+) and the cathode as (-). | Answers to question 9 | |
| Alternative | Statement 1 <i>Assertion</i> | Statement 2 <i>Reason</i> | Alternative | | n | % |
| a* | True | True | a | 27 | 29.4 | |
| b* | True | True | b | 13 | 14.1 | |
| c | True | False | c | 6 | 6.5 | |
| d | False | True | d** | 42 | 45.7 | |
| e | False | False | e | 4 | 4.3 | |

*The difference between alternatives *a* and *b* was explained before the test. In both cases statements 1 and 2 are both true, but in *a* the reason statement correctly explains the assertion and in *b* it does not.

**Correct answer

while in electrolytic cells oxidation occurs at the cathode and reduction at the anode” was thought to be true by half of the respondents who chose either ‘a’, ‘b’ or ‘c’. They held misconception 6.

Several previous studies^{19, 22-24} about the students’ understanding of electrochemistry reported that the students have the incorrect idea: “*In galvanic cells, the anode is positively charged because it has lost electrons; the cathode is negatively charged because it has gained electrons*”. This alternative idea did not appear as a common misconception among the subjects of this study; the number of students holding this view was only ten. However, responses to a question showed that a significant proportion (41%) believed that in galvanic cells, the electrodes are charged with a high electrical charge. This was regarded as a new misconception (7, Appendix). This finding is consistent with the results of previous research. Sanger and Greenbowe²⁴ reported that students overestimate the magnitude of the net charge associated with the electrodes. They analyzed ten college-level chemistry textbooks and stated that only one of these books discusses the net charges of the electrodes in a galvanic cell, and it mentions that the net charge on the electrodes is exceedingly small – only about one electron for 10^{14} metal atoms.

In another question, the assertion statement “*In an electrolytic cell, the direction of the applied voltage has no effect on the reaction or the site of the anode and cathode*” was a previously reported misconception (8, Appendix).^{19, 22, 24} Half of our subjects showed that they held this misconception by choosing the statement as true. On the other hand, the statement “*In both electrolytic and galvanic cells, oxidation occurs at the anode and reduction at the cathode*” was the reason in the question. Forty-one subjects (45 %) thought the reason statement was false. This is consistent with the subjects’ responses to question 9 since the assertion statement in this question was thought to be true by half of the respondents. Forty-one subjects probably had the idea that in electrolytic cells oxidation occurs at the cathode and reduction at the anode. Therefore it may be assumed that they also held misconception 6.^{19, 22, 24}

Sanger and Greenbowe²⁴ reported that the misconception “*The identity of the anode and cathode depends on the placement of the half-cells*” was originally suggested by a student who observed that the textbook and the instructor always drew the anode half-cell on the left and the cathode half-cell on the right. They suggested that while it may seem logical for authors and instructors to consistently place the anode half-cell on the left-side according to the cell notation suggested by IUPAC and

always to connect it to the (–) terminal of the voltmeter, this may mislead students into believing that these are viable methods to identify the anode and cathode in electrochemical cells. They suggested that these conventions might pose problems when students are asked to analyze electrochemical cell diagrams in examinations or build and draw cells in the laboratory. The results of this study are in accordance with their findings. In response to a question, forty-seven subjects believed that the identity of the anode and cathode of a galvanic cell shown in a figure depends on the physical placement of the half-cells (misconception 9). Moreover, of the forty-seven subjects having this idea, twenty-six (55%) believed that the statement “*IUPAC convention requires to place the cathode on the right and the anode on the left in the cell notation*” correctly explained their belief. This alternative idea was regarded as a new misconception (10, Appendix).

Metallic and electrolytic conduction

In response to a question designed to probe the students’ understanding of metallic conduction, twenty-three subjects (25%) stated that in a galvanic cell electrons enter the electrolyte at the cathode, move through the electrolyte and emerge at the anode. Fourteen of these subjects believed that the statement “*Electrons move directly from the anode to cathode through the external circuit*” correctly explains their idea. This demonstrated two previously identified misconceptions (11 and 12, Appendix). In response to another question, fifty-two subjects (57%) claimed that in an electrolytic cell free electrons move both in the electrolyte and in the wire connecting the two electrodes because they conduct an electric current through the circuit. This was regarded as a new misconception (13, Appendix).

In Question 15 (Table 3) both statements are false, but thirty-six subjects marked ‘a’. They believed that if a metal wire replaces the salt bridge in a galvanic cell, the ammeter connected through the circuit will show a reading because there will be continuous flow of current, since the metal wire conducts electricity. This alternative idea was a new misconception labelled as 14. On the other hand, twelve subjects marked ‘b’, having the idea that both statements are true, but that there is not an assertion-reason relationship between them. Sixty-seven subjects thought that if a metal wire replaces the salt bridge in the galvanic cell, the ammeter connected through the circuit would show a reading. This misconception was also identified as new (15, Appendix). Those, who thought the reason statement was true, probably had the incorrect idea that in galvanic cells the salt bridge supplies electrons to complete the circuit. Therefore they

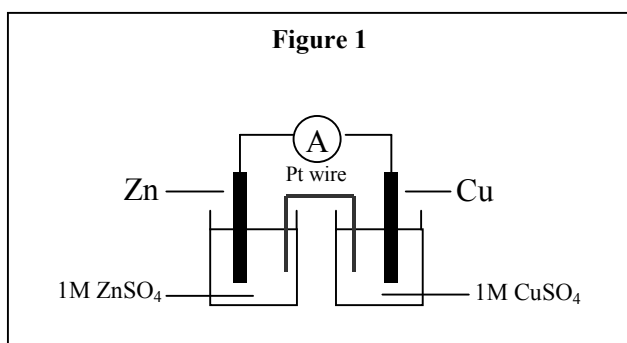
Table 3

Question 15

| Assertion | | <i>because</i> | Reason | | |
|---|---------------------------------|------------------------------|---|----|------|
| The ammeter connected through the circuit in Figure 1 will show a reading | | | There will be a continuous flow of current since the platinum wire conducts electricity | | |
| Answers to question 15 | | | | | |
| Alternative | Statement 1 <i>Assertion</i> | Statement 2 <i>Reason</i> | Alternative | n | % |
| a* | True | True | a | 36 | 39.1 |
| b* | True | True | b | 12 | 13.0 |
| c | True | False | c | 19 | 20.7 |
| d | False | True | d | 8 | 8.7 |
| e | False | False | e** | 17 | 18.5 |

*The difference between alternatives *a* and *b* was explained before the test. In both cases statements 1 and 2 are both true, but in *a* the reason statement correctly explains the assertion and in *b* it does not.

**Correct answer



can be assumed to demonstrate misconception 16 (Appendix).

In response to the question “*What does the salt bridge do?*”, of the fifteen subjects interviewed, four stated that the salt bridge completes the circuit but this does not necessarily mean that it assists the flow of current; the ions assist the flow of current. The results of the test were in accordance with the responses in the interviews. In a test question, forty-two respondents thought the statement “*the salt bridge assists current flow*” to be false. This resulted in a new, surprising, misconception (17, Appendix).

In a test question, the assertion statement “*In the electrolysis of aqueous Na₂SO₄ with inert electrodes H₂(g) is produced at the cathode and O₂(g) at the anode*”, was true and the reason statement “*The movement of Na⁺ and SO₄²⁻ ions in solution does not constitute an electric current*” was false. Unfortunately, forty-three subjects (47%) thought the reason statement to be true. They seemed to believe that the movement of sodium and sulphate ions does not constitute an electric current because they do not react at the electrodes. This led to the identification of a new misconception not previously reported (18).

Chemical and electrochemical equilibrium

Question 18 and the percentage of respondents who chose each alternative in this item are given in Table 4. In this question, the assertion statement “*When a metal is immersed in an electrolyte involving its ions, the electrical potentials of the metal and electrolyte become equal*” was false and the reason statement “*An electrochemical equilibrium is established between the metal and ions in the electrolyte when a metal is immersed into an electrolyte involving its ions*” was true. Forty-nine of the subjects thought the assertion statement to be true by choosing either ‘a’, ‘b’, or ‘c’. They held a new misconception (19, Appendix). Of the forty-nine who held this misconception, thirty thought that the reason statement correctly explained the assertion statement. Their alternative idea was regarded as another misconception (20). Previous studies did not investigate chemical and electrochemical equilibrium, whereas the present one took these concepts into account. The students’ other misconceptions about chemical and electrochemical equilibrium were reported and discussed in detail in the earlier paper.²⁸

Predicting the electrode and cell reactions

In the course of the interviews, five of the fifteen subjects surprisingly claimed that the reduction and oxidation of the species in the electrolyte do not occur at the electrodes; these reactions occur at metal/solution interfaces. The results from the analysis of two test questions were consistent with the subjects’ responses in the interviews. In response to one of these questions, fifty-two of the subjects chose as true that “*No reaction occurs at the electrodes if inert electrodes are used in a galvanic cell because inert electrodes are not altered chemically in cell reactions*”. In response to

Table 4

Question 18

| Assertion | | | <i>because</i> | Reason | | |
|---|---------------------------------|------------------------------|------------------------|---|------|--|
| When a metal is immersed in an electrolyte containing its ions, the electrical potentials of the metal and the electrolyte become equal | | | | When a metal is immersed in an electrolyte containing its ions, an electrochemical equilibrium is established between the metal and its ions in the electrolyte | | |
| Alternative | Statement 1 <i>Assertion</i> | Statement 2 <i>Reason</i> | Answers to question 18 | | | |
| | | | Alternative | n | % | |
| a* | True | True | a | 30 | 32.6 | |
| b* | True | True | b | 3 | 3.3 | |
| c | True | False | c | 16 | 17.3 | |
| d | False | True | d** | 40 | 43.5 | |
| e | False | False | e | 3 | 3.3 | |

*The difference between alternatives *a* and *b* was explained before the test. In both cases statements 1 and 2 are both true, but in *a* the reason statement correctly explains the assertion and in *b* it does not.

**Correct answer

another question, fifty-six subjects (61%) had the similar idea that “*In electrolytic cells, no reaction occurs at the anode if an inert electrode is used as the anode because inert electrodes are not oxidized in cell reactions*”. These led to the identification of a new misconception (21, Appendix). The students who demonstrated misconception 21 presumably recognized only the reactions of the electrode material as electrode reactions. These subjects seemed to be unaware that all electrode reactions, whether they involve the electrode material or not, are considered to occur at the electrodes (i.e. at the interface between the electrode and electrolyte). Textbook authors or instructors should note that the term ‘electrode’ usually refers to a metallic conductor; however, in some cases it refers to a half-cell and even to the interfacial region. As

discussed before by Sanger and Greenbowe,²⁴ some textbooks never specify the composition of inert electrodes and fail to mention that, although these electrodes made of inert substances and therefore are unreactive towards oxidation and reduction, it is possible for the other electrodes to react. On the other hand, most of the textbooks do not discuss why some electrodes are inert while others can react. As a result, students have difficulty in determining when an electrode will be reactive or inert. Instructors and textbook authors need to discuss some of the factors that make electrodes inert.

In the course of the interviews, three subjects stated that “*water does not react during the electrolysis of aqueous solutions*”. This scientifically incorrect

Figure 5

Question 25

| Assertion | | | <i>because</i> | Reason | | |
|--|---------------------------------|------------------------------|------------------------|---|------|--|
| If the electrolysis of water is attempted, using inert electrodes, essentially no reaction is observed at the electrodes | | | | Water does not react during the electrolysis of aqueous solutions | | |
| Alternative | Statement 1 <i>Assertion</i> | Statement 2 <i>Reason</i> | Answers to question 25 | | | |
| | | | Alternative | n | % | |
| a* | True | True | a | 14 | 15.2 | |
| b* | True | True | b | 28 | 30.4 | |
| c | True | False | c** | 24 | 26.1 | |
| d | False | True | d | 8 | 8.7 | |
| e | False | False | e | 18 | 19.6 | |

*The difference between alternatives *a* and *b* was explained before the test. In both cases statements 1 and 2 are both true, but in *a* the reason statement correctly explains the assertion and in *b* it does not.

**Correct answer

idea was included in Question 25 (Table 5) as the reason statement. The results of the test are in accordance qualitatively with the responses in the interviews. Fifty subjects who chose 'a', 'b', or 'd' thought the above reason statement was true; this led to the identification of a previously reported^{19, 22, 24} misconception (22). Misconception 23, reported previously by Sanger and Greenbowe²⁴ "In electrolytic cells with identical electrodes connected to the battery, the same reactions occur at each electrode" was also held by two of the fifteen students interviewed. Subsequently, this mistaken idea was included in Question 26 (Table 6). However, it did not appear as a common misconception among the subjects of this study; only four subjects marked 'a', 'b', or 'c', as shown in Table 6. This is probably due to the fact that during their practical work in the electrochemistry laboratory, these students had carried out the electrolysis of sulfuric acid solution with inert (Pt) electrodes and determined the Faraday constant from the volume of the electrolysis products [O₂(g) and H₂(g)] and the amount of electricity that passed through the electrolyte.

Conclusions

This study was able to identify new student misconceptions concerning electrochemistry related to galvanic and electrolytic cells. In addition, it confirmed some of the previously reported misconceptions. However, the fact that the subjects of this study did not hold some of the previously reported misconceptions does not necessarily mean that the here-unseen misconceptions are not valid or common. Moreover, some of the misconceptions here identified may be specific to this group of students.

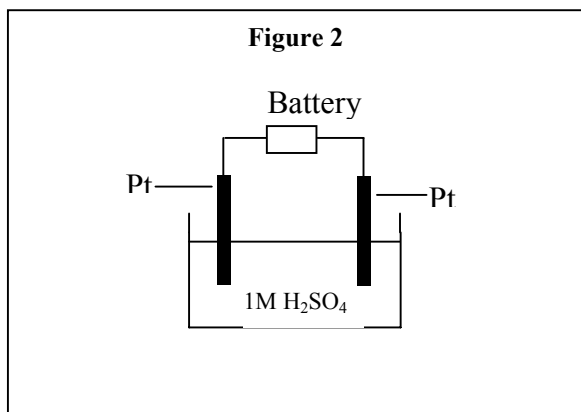
Although the subjects of this study received an intensive classroom and laboratory instruction on electrochemistry for several months, the results of this study demonstrated that the students still had many misconceptions about the basic aspects of electrochemistry. Some of these are similar to those of students at different education levels and countries. This is consistent with the constructivist model of learning, which suggests that the source of

Table 6

| Assertion | | | because | Reason | | |
|--|---------------------------------|------------------------------|-------------|--|-------------------------------|---|
| In the cell shown in Figure 2 the same reaction occurs at each electrode | | | | The two electrodes in the cell are identical | Answers to question 26 | |
| Alternative | Statement 1 <i>Assertion</i> | Statement 2 <i>Reason</i> | Alternative | | n | % |
| a* | True | True | a | 2 | 2.2 | |
| b* | True | True | b | 2 | 2.2 | |
| c | True | False | c | 0 | 0 | |
| d | False | True | d** | 86 | 93.4 | |
| e | False | False | e | 2 | 2.2 | |

*The difference between alternatives *a* and *b* was explained before the test. In both cases statements 1 and 2 are both true, but in *a* the reason statement correctly explains the assertion and in *b* it does not.

**Correct answer



students' alternative conceptions lies in how they construct knowledge; when students construct their own meanings they are influenced by their existing (often incorrect) conceptions (Osborne and Wittrock²⁹). During the learning process, the students have previously constructed frameworks of conceptions in their memory and recall these to interpret the new knowledge from the lecture.

A significant proportion of our subjects were capable of solving various complex electrochemistry problems during their course. However, they could not demonstrate satisfactory knowledge about the basic concepts of electrochemistry. It was stated in several reports that most of the assessments of chemistry or

electrochemistry courses in various countries are based on quantitative problem-solving abilities (Nurrenbern and Pickering,³⁰ Pickering,³¹ Sawrey,³² Ogude and Bradley²⁰). Unfortunately the situation for the subjects of this study is no different; the electrochemistry course and the examinations emphasized the quantitative and mathematical aspects of the subject. One of the difficulties with this approach is that students learn by rote-application of algorithms the facility to carry out calculations but they do not need to construct proper meanings for the ideas involved in the calculations. Probably there were no opportunities to elicit the students' qualitative explanations, to find out what alternative ideas they had before they started the course and what alternative ideas they developed during the course. Instead, they learnt to manipulate symbols and equations to solve quantitative electrochemistry problems without understanding the concepts they represented. By presenting electrochemical concepts only in terms of mathematical relationships, students are allowed to ignore the conceptual meaning of the equations while they concentrate on using them to perform calculations. This type of presentation may mislead students into believing that conceptual knowledge is not important or even necessary to be successful in an electrochemistry course.

It seems that another influence on the students' learning difficulties is the style of examination questions. Nearly all the students had the same reaction to the assertion-reason questions with true-false alternatives. They said that these questions were very different from those they had faced in their electrochemistry course and exams. Our results suggest that questions employed in the electrochemistry teaching and assessment process need to be of a kind that requires students demonstrate an understanding of basic concepts and that the teaching should be revised to prepare students for these. The setting of questions involving only numerical calculations gives the impression that competence in manipulating equations is all that is needed to learn the subject. In this study, the disregard of the conceptual knowledge during the teaching and especially assessment processes seemed to be the main reason for the students' misconceptions in electrochemistry. Instructors probably teach, but underemphasize conceptual knowledge and they usually do not assess it. Therefore, students realize that it is the assessment that counts, and concentrate their efforts on improving their problem solving abilities.

As also reported in the earlier paper,²⁸ the results of this study showed that one of the difficulties experienced by our subjects involved the concept of different potentials. The students have difficulty

understanding that the half-cell potential talked about in electrochemistry is the potential difference between the solution and the electrode immersed in it, and this potential difference can not be measured but the difference between two differences, or the potential difference between two half-cells, can. Therefore, it is strongly recommended that instructors or curriculum developers offer detailed explanation of the origin of half-cell potentials (the interactions between the metal atoms on the electrode and the metal ions in solution, the electrical double layer, and the formation of a potential difference at two metal-solution interfaces during the approach to equilibrium). Moreover, they should explain clearly the instrumental requirements for the measurement of the potential difference between two electrodes under the conditions of no current flow (cell emf) and the changes in circuitry required for current to pass through an electrochemical cell. This explanation should include the relations between the use of a specially designed voltmeter (potentiometer) to measure the cell emf, the current flow in a cell, and chemical and electrochemical equilibrium. In that way, students can be able to understand what the terms 'chemical equilibrium' and 'electrochemical equilibrium' refer to in electrochemical processes, and what the relationship and difference between these are.

Various concepts relevant to cells, such as electrode potential, electrical double layer, cell emf, chemical and electrochemical equilibrium, current, electrical conductance (metallic and electrolytic conductance), electrical neutrality, salt bridge, and electrode processes cannot be understood in isolation from each other. An instructional strategy aimed at alleviating students' misconceptions about these concepts should thus adopt an approach where the cell can be understood in its entirety. For example, the lack of knowledge of what individual components of a galvanic cell do can lead to various misconceptions; a formal description of what a very high resistance voltmeter (potentiometer), ammeter, salt bridge, and external source of current do in a circuit can alleviate this problem.

As stated in the results and discussion part, there was widespread uncertainty about why the potential of standard hydrogen electrode is set at 0.00 V, so the students proposed a variety of reasons during the interviews. Moreover, as identified in this study and previously by Sanger and Greenbowe,²² many students do not understand that chemists cannot make absolute potential measurements. On the other hand, they think that there is a relationship between the half-cell potentials and the spontaneity of half-cell reactions. On the basis of these findings, we suggest that instructors should

emphasize the role of the standard hydrogen electrode or other reference electrodes in determining half-cell potentials and the relative nature of these potentials. As reported by Sanger and Greenbowe,²² although all textbooks usually contain explicit statements that absolute half-cell potentials can not be measured, some of these contain statements suggesting that standard reduction potentials are absolute — that is, half-reactions with positive reduction potentials are spontaneous and half-reactions with negative reduction potentials are nonspontaneous and spontaneous in the opposite direction. On the other hand, some textbooks calculate cell potentials using the equation $E_{\text{cell}}^0 = E_{\text{red}}^0 + E_{\text{ox}}^0$, where E_{red}^0 is the reduction potential of the reduction half-reaction and the E_{ox}^0 value is determined by taking the reduction potential of the oxidation half-reaction and changing its sign. Although this is technically the same as calculating the cell potential as a potential difference (i.e., $E_{\text{cell}}^0 = E_{\text{cathode}}^0 - E_{\text{anode}}^0$, where E_{cathode}^0 and E_{anode}^0 are the standard reduction potentials of the reduction and oxidation half-reactions, respectively), calculating the cell potential as a sum may mislead students into believing that these potentials are absolute. An additional problem may arise from using the additive method. Although the equation, $E_{\text{cell}}^0 = E_{\text{red}}^0 + E_{\text{ox}}^0$, works only for balanced oxidation-reduction reactions, students may get the impression that the standard oxidation and reduction potentials for any half-reactions are extensive properties that obey Hess's Law, and can be added together. For example, they may believe that $E_{\text{red}}^0(\text{Cu}^{2+}/\text{Cu}^+)$ can be calculated by adding $E_{\text{red}}^0(\text{Cu}^{2+}/\text{Cu})$ to $E_{\text{ox}}^0(\text{Cu}/\text{Cu}^+)$. Therefore, using the additive method may reinforce the relevant student misconceptions; it is strongly recommended that instructors calculate cell potentials using the potential difference method.

It may be concluded from the results of this and previous studies¹⁶⁻²² that an effective teaching strategy aimed at improving students' understanding of galvanic and electrolytic cells should take into consideration documented misconceptions about electrochemistry, their likely origins, and suggestions to overcome these proposed in previous research on the topic. We believe that the application of carefully designed conceptual explanations based on research findings, while providing students with accurate information, is indispensable in achieving this goal. On the other hand, the use of carefully designed conceptual questions during or after the presentation of conceptual explanations may help them to construct their knowledge properly. Moreover, some assessment at the beginning of the teaching process may be useful to evaluate the nature of the knowledge students bring to the class. This could

give an instructor a focus for where particular instruction will be needed to overcome students' misconceptions. The explicit teaching of structural knowledge of concepts requires the students to actively engage in the teaching-learning process. During this process, conceptual questions can be utilized to create a class discussion, encourage the students to actively engage the discussion, and therefore to facilitate conceptual change. The students should be allowed to express and defend their judgement to the class. Once the students have made their effort to express and defend their alternative ideas, it is the instructor's turn. The instructor's effort should consist in being prepared to promote and steer class discussion by considering students' alternative ideas. He or she should never forget to tie all the loose ends together by providing the authoritative explanation of the events. On the other hand, instructors should use a carefully chosen terminology and avoid insufficient explanation in explaining electrochemical processes. For instance, one of the difficulties students have in dealing with the identification of the correct direction of ion and electron flow in cells using electrode charges. Although the net charges on the electrodes are extremely small and simple electrostatic arguments concerning these charges do not correctly explain the correct direction of ion and electron flow, they routinely apply simple electrostatic arguments to determine the direction of electrically charged species. Therefore, they have difficulty understanding the following points:

- Why do electrons flow away from a positively charged anode toward a negatively charged cathode in electrolytic cells?
- Why do anions flow toward a negatively charged anode and cations move toward a positively charged cathode in galvanic cells?
- Why is the cathode labeled (+) in a galvanic cell although the electrons move from the anode to the cathode?

A detailed description of the net electronic charges on the electrodes, emphasizing that the net charge on each electrode is exceedingly small and simple electrostatic arguments can not be used to determine the direction of ion and electron flow, will probably minimize students' mistaken beliefs about this area. On the other hand, instructors who have the idea that this description is too complex for some students to understand may choose to emphasize the electrode signs as electrode polarities (i.e., the positive electrode has a higher potential than the negative electrode) instead of electronic charges.

Conceptual computer animations that portray the electrochemical processes occurring in the half-cells at the molecular level may be used in conjunction with electrochemistry lectures. In that

way, students may be able to make better connections between the microscopic and macroscopic levels of knowledge and explore specific aspects of the cells in more detail, after viewing a molecular level representation of the dynamics of the cells, such as ion migration in solution in the anode and cathode compartments and the salt bridge, electron movement in the external circuit, reduction at the cathode, and oxidation at the anode. However, it should be noted that using computer animations does take some additional time and may not be practicable in some developing countries, due to economical shortages and/or crowded classes. In the absence of available computer technology, carefully designed models may be developed and used to contribute to students' ability to visualize molecular behaviour in electrochemical processes occurring in a cell.

Because of these findings, the authors of this study plan to change the method of teaching about galvanic and electrolytic cells in a university general chemistry course. An experimental group will be told about the known misconceptions and why these statements are considered incorrect. During the teaching process with this group, conceptual questions carefully designed on the basis of previous research findings will be applied to improve the students' conceptual understanding of electrochemical processes and their problem solving ability. A control group will be taught in the traditional manner. The achievement of two groups both in conceptual knowledge and in problem solving ability will be compared statistically, to assess the ability of this instructional method to prevent and overcome misconceptions. Several reports have shown that when students are taught chemical processes conceptually and assessed accordingly, their conceptual knowledge improves considerably (Pickering,³¹ Burke et al.³³).

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Appendix

Misconceptions identified in this study^{a, b}

Electrode potentials and cell emf

1. Half-cell potentials can be used to predict the spontaneity of the half-cell reactions
2. *Half-cell potentials can be used to predict the spontaneity of the half-cell reactions because some half-cell potentials are positive while the others are negative in value.*
3. *Electrode potential is equal to the electrochemical potential difference between the metal and electrolyte in the half-cell.*
4. The value of zero for the standard potential of the $H_2(1 \text{ atm})/H^+(1M)$ standard half-cell is zero is somehow based on the chemistry of H^+ and H_2 .
5. *The value of zero for the standard potential of the $H_2(1 \text{ atm})/H^+(1M)$ standard half-cell is zero is somehow based on the chemistry of H^+ and H_2 because hydrogen is in the middle of the activity series for metals.*

Identifying the anode and cathode

6. Processes at the anode and cathode are reversed in galvanic and electrolytic cells; in galvanic cells oxidation occurs at the anode and reduction at the cathode, while in electrolytic cells oxidation occurs at the cathode and reduction at the anode.
7. *In galvanic cells, the electrodes are charged with a high electrical charge.*
8. In an electrolytic cell, the direction of the applied voltage has no effect on the reaction or the site of the anode and cathode.
9. In galvanic cells, the identity of the anode and cathode depends on the physical placement of the half-cells.
10. *In galvanic cells, the identity of the anode and cathode depends on the physical placement of the half-cells because IUPAC convention requires the placing of the cathode on the right and the anode on the left in the cell notation.*

Metallic and electrolytic conduction

11. Electrons flow in electrolytes.
12. Electrons enter the electrolyte at the cathode, move through the electrolyte, and emerge at the anode.
13. *In an electrochemical cell free electrons are found both in the electrolyte and in the wire connecting two electrodes because they conduct an electric current throughout the circuit.*
14. *If a metal wire replaces the salt bridge in a galvanic cell, the current continues to flow because the metal wire conducts electricity.*
15. *If a metal wire replaces the salt bridge in a galvanic cell, the ammeter connected through the circuit will show a reading.*
16. In galvanic cells, the salt bridge supplies electrons to complete the circuit.
17. *The salt bridge does not assist current flow.*
18. The movement of an ion in solution does not constitute an electric current if it does not react at the electrodes.

Chemical and electrochemical equilibrium^c

19. *When a metal is immersed in an electrolyte involving its ions, the electrical potentials of the metal and electrolyte become equal.*
20. *When a metal is immersed into an electrolyte involving its ions, the electrical potentials of the metal and electrolyte become equal because an electrochemical equilibrium is established between the metal and its ions in the electrolyte.*

Predicting the electrode and cell reactions

21. *No reaction occurs at the electrodes if inert electrodes are used in a galvanic or an electrolytic cell because inert electrodes are not altered chemically in cell reactions.*
22. Water does not react during the electrolysis of aqueous solutions.
23. In electrolytic cells with identical electrodes connected to the battery, the same reactions occur at each electrode.^d

^a Misconceptions reported by Garnett and Treagust^{18, 19} and Sanger and Greenbowe²²⁻²⁴

^b Italicized misconceptions are new ones, reported for the first time in this paper.

^c The students' other misconceptions about chemical and electrochemical equilibrium were reported and discussed in detail in an earlier paper (Özkaya²⁸).

^d It was expected that a significant proportion of the students would demonstrate this misconception, but they did not.