Students' Misconceptions in Electrochemistry: Current Flow in Electrolyte Solutions and the Salt Bridge[1]

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Several researchers have documented students' misconceptions in electrochemistry. One reason for the interest in studying electrochemistry is that surveys of students and teachers suggest that students find this topic difficult (*1*), and research confirms that students' beliefs about problem complexity affect their performance and learning (*2*). Several articles have promoted pedagogical suggestions or opinions about more effective methods of teaching electrochemistry (*3–6*); but few, if any, of these have actually been tested.

Allsop and George (*7*) reported that students had difficulty using standard reduction potentials to predict the direction of chemical reactions and were unable to produce an acceptable diagram of an electrochemical cell; 11% of these students stated that a salt bridge provides a pathway for the flow of electrons. Ogude and Bradley (*8*) noted that although many students can solve the quantitative electrochemical problems that appear on chemistry exams, few were able to answer qualitative questions requiring a deeper conceptual knowledge of electrochemistry. Also in this study, 30% of college students consistently replied that electrons cannot flow in the electrolyte and 28% consistently replied that electrons can flow in the electrolyte; 42% were inconsistent in their responses. Similar results were found in the 25th National Youth Science Olympiad in South Africa in 1989 (*8*): 30% of students suggested that ions flow to complete the circuit in the electrolyte solution, while 61% suggested that electrons flow in the electrolyte.

Garnett and Treagust (*9, 10*) probed student misconceptions about oxidation–reduction reactions and electrochemical and electrolytic cells through interviews with high-school students in Australia. They reported several common misconceptions about oxidation–reduction reactions, electrochemical cells, and electrolytic cells. Misconceptions about the flow of current in electrolyte solutions and the salt bridge include the notions that (i) electrons move through the electrolytes and the salt bridge, carried or transferred by cations and anions; (ii) protons move through the electrolytes and the salt bridge, even in neutral or basic solutions; and (iii) ion movements in solution do not constitute an electrical current. Garnett et al. (*11*) discussed some probable origins of these misconceptions and their implications for improving the chemistry curriculum.

We have replicated, with additions, Garnett and Treagust's interview study (*10*) to probe students' misconceptions about galvanic (electrochemical), electrolytic, and concentration (Nernst) cells. We reported the responses of 16 student volunteers (9 men and 7 women) from three freshman-level chemistry courses at a Midwestern American university (*12*). The first part of this article focuses on students' misconceptions and proposed mechanisms related to current flow in electrolyte solutions and the salt bridge (summarized in Table 1), and on likely sources for these misconceptions. The second part reports the results of a study to determine whether teaching to actively confront the misconception that electrons flow in solution using computer animations will decrease the number of students consistently harboring this misconception.

Current Flow through Electrolyte Solutions and the Salt Bridge

In general, students recognize that current cannot flow without a closed circuit, and many believe that only electron flow can complete this circuit. Consequently, many students cling to the notion that electrons flow from the anode to the cathode along the wire and are then released into the electrolyte at the cathode, traveling through the electrolyte solutions and the salt bridge to reach the anode. This is represented as *Misconception 10a*[2] (electrons enter the solution from the cathode, travel through the solutions and the salt bridge, and emerge at the anode to complete the circuit), which was held in one form or another by 9 of the 16 students.

Of those who believed that electrons flow through the salt bridge, two stated that anions in the electrolyte solutions and the salt bridge help transfer the electrons (*Misconception 10b*: anions in the salt bridge and the electrolyte transfer electrons from the cathode to the anode); three stated that cations transfer the electrons through the salt bridge (*Misconception 10c*: cations in the salt bridge and the electrolyte accept electrons and transfer them from the cathode to the anode); and three stated that the electrons flow through solution without any assistance from anions or cations (*Misconception 10e*: electrons can flow through aqueous solutions without assistance from the ions).

Three students who correctly stated that ions flow through solutions and the salt bridge to complete the circuit suggested that it is the flow of *anions* in solution that completes the circuit, and *cation* flow does not constitute a current (*Misconception 10f*: only negatively charged ions

Table 1. Common Student Misconceptions

No.	Statement of Misconception
2h	Electrons move through solution by being attracted from one ion to the other.
2i	Electrons move through solution by attaching themselves to ions at the cathode and are carried by that ion to the anode.
10a	Electrons enter the solution from the cathode, travel through the solutions and the salt bridge, and emerge at the anode to complete the circuit.
10b	Anions in the salt bridge and the electrolyte transfer electrons from the cathode to the anode.
10c	Cations in the salt bridge and the electrolyte accept electrons and transfer them from the cathode to the anode.
10e[a]	Electrons can flow through aqueous solutions without assistance from the ions.
10f[a]	Only negatively charged ions constitute a flow of current in the electrolyte and the salt bridge.
11b	The anode is positively charged because it has lost electrons; the cathode is negatively charged because it has gained electrons.

[a] Not previously reported by Garnett and Treagust (*9, 10*).

constitute a flow of current in the electrolyte and the salt bridge).

In their responses to questions about electrochemical and electrolytic cells, 7 of the 16 students responded with comments suggesting that the electrodes have net positive and negative charges. Some who believed that the anode is positively charged held *Misconception 11b* (the anode is positively charged because it has lost electrons; the cathode is negatively charged because it has gained electrons); they interpreted anion flow toward the anode as suggesting that the anode is positively charged and cation flow toward the cathode as suggesting that the cathode is negatively charged.

Mechanisms for Electron Transfer through Electrolyte Solutions and the Salt Bridge

Eight of the nine students who stated that electrons flow in electrolyte solutions and the salt bridge suggested possible mechanisms for the flow of electrons. Five stated that electrons are transferred from cathode to anode by the ions in solution (*Misconception 2i*: electrons move through solution by attaching themselves to ions at the cathode and are carried by that ion to the anode). Four of these students stated that cations (Ag^+ and K^+ in the galvanic cell and Al^{3+} in the electrolytic cell) assisted in the transfer of electrons from cathode to anode (*Misconception 10c)*, while one student stated that anions help in the transfer of electrons from cathode to anode. None of the students in this study demonstrated *Misconception 2h* (electrons move through solution by being attracted from one ion to the other). This misconception was originally reported by Garnett and Treagust (*9*): a student suggested that electrons are transferred back and forth from anion to cation as they travel from cathode to anode in solution. Three students who stated that electrons flow in electrolyte solutions and the salt bridge suggested that the electrons receive no assistance from ions and travel as free electrons from the cathode to the anode (*Misconception 10e*).

In contrast to Garnett and Treagust's students (*9*), none of our students suggested that electrons in solution are transferred from the cathode to the anode by "piggy-backing" from anions to cations (*Misconception 2h*), and several of our students suggested that electrons travel in solution as free electrons from the cathode to the anode (*Misconception 10e*). While these differences are interesting, we are unable to attribute them to developmental (high school versus college) or pedagogical (teaching methods in Australia versus those in the United States) differences.

Probable Sources of Misconceptions

Garnett and Treagust (*10*) proposed two origins of student misconceptions concerning the flow of current in electrolyte solutions and the salt bridge: (i) students' interpretation of the language of science—students interpret the terminology used in the textbook or by the instructor in a manner consistent with everyday usage, but inconsistent with scientific usage; and (ii) students applying information too generally, over-generalizing a scientific statement to situations where it is inappropriate. From these proposed origins, Garnett et al. (*11*) drafted suggestions for improving the chemistry curriculum that included the following ideas: (i) teachers and curriculum developers need to select explanatory language with care, and be particularly cautious in selecting language having everyday meanings that differ from meanings in a scientific context; and (ii) teachers and curriculum developers need to be cautious in making unqualified, generalized statements about concepts because students tend to interpret the statements literally, and apply them more extensively than is intended.

Ogude and Bradley (*8*) attributed student misconceptions concerning current flow in electrolyte solutions and the salt bridge to two factors: (i) reference by textbooks or the instructor to continuity of current and established belief in the electronic nature of current electricity (phrases like "continuity of current" imply that current is uniform throughout the electrochemical cell); and (ii) careless discussion of electrode processes (textbooks with obvious mistakes or misleading statements result in student misconceptions).

Both Garnett and Treagust (*9, 10*) and Ogude and Bradley (*8*) suggested that a major source of misconceptions comes from imprecise or inappropriate language used by textbooks and instructors in explaining electrochemical concepts and this study is no exception. More than half the students (9 of 16) in this interview study suggested that electrons flow in electrolyte solutions and the salt bridge to complete the circuit. Analysis of the three textbooks used by these students (*14–16*) revealed that all have comments that, while not technically incorrect, may be misinterpreted to suggest that electrons do flow through electrolyte solutions and the salt bridge. For example:

1. In a molten salt such as sodium chloride, or in a solution of an electrolyte, however, electrical charge is carried through the liquid by the movement of ions. The transport of electrical charge by ions is called **electrolytic conduction**, and it is able to occur only when chemical reactions take place at the electrodes. (*14*, p 770)

   Comment: If students interpret "electrical charge" as "electrons" instead of as "the inherent charge of the ions", the first sentence could lead to *Misconceptions 10b* and *10c* and the second sentence could foster *Misconception 2i* about the transfer of electrons through electrolyte solutions and the salt bridge.

2. ...This task is accomplished through a **voltaic** (or **galvanic**) **cell**, which is merely a device in which electron transfer is forced to take place through an external pathway rather than directly between reactants. (*15*, p 727)

   Comment: Electrons are being transferred from the reductant to the oxidant, but "electron transfer through an external pathway" can be misinterpreted as suggesting that electrons flow throughout the entire circuit including the electrolyte solutions and the salt bridge and may be responsible for *Misconceptions 10a* or *10e*.

3. ...If we physically separate the oxidizing agent from the reducing agent, the transfer of electrons can take place via an external conducting medium. As the reaction progresses, it sets up a constant flow of electrons and hence generates electricity (that is, it produces electrical work). (*16*, p 767)

   Comment: The "constant flow of electrons" occurs only in the wire connecting the electrodes, but student may over-generalize this statement to the flow of current in electrolyte solutions and the salt bridge, which would result in *Misconceptions 10a–e*.

The results of this analysis should prompt textbook authors to carefully examine and reconsider the language used in their chemistry textbooks. The use of detailed diagrams and animations about current flow through electrolyte solutions and the salt bridge should be included in a multimedia presentation to help students visualize these concepts. Park and Hopkins (*17*) report that dynamic visual displays are more effective than static ones.

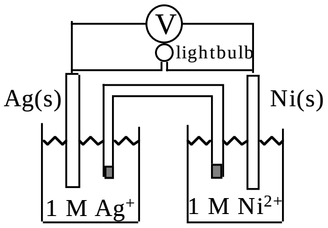
Some Methods for Preventing Misconceptions

We have become increasingly interested in the use of computer animations as a lecture tool to enhance students' ability to visualize and understand chemical concepts on the molecular level. In a typical lecture, the instructor performs a live chemical demonstration, writes the relevant balanced chemical equation(s) on the chalkboard, and shows and explains a computer animation depicting the reaction on the molecular level. In this way, the lecture attempts to facilitate students' connection of the macroscopic, symbolic, and microscopic representations of chemical processes (*18–20*). Examples of electrochemistry animations used in these lectures have been reported by Greenbowe (*21*).

Preliminary studies to determine whether we can reduce the number of students holding the misconception that electrons flow in the salt bridge by teaching to actively confront, and therefore prevent or dispel, this misconception are encouraging. After receiving instruction on electrochemistry, students in the second semester of introductory chemistry for non-science majors answered three conceptual questions about the flow of electrons in electrolyte solutions and the salt bridge (Fig. 1). The instructor had explicitly emphasized that electrons do *not* flow in electrolyte solutions or the salt bridge and showed several computer animations that modeled the correct flow of current in galvanic and electrolytic cells (i.e., electron flow in the wires and cation and anion flow in the electrolyte solutions). Table 2 contains a description and an approximate running time of the computer animations employed. Each one was displayed three times in succession while the instructor provided a narration of events. Presenting visual and verbal (oral and written) information simultaneously is consistent with Paivio's dual coding theory (*22*) and Mayer and Anderson's contiguity principle (*23*).

1. Electrons in the cell flow through the ___ toward the ___.

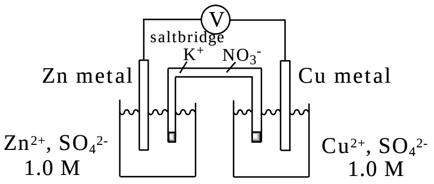
   (1) wire, silver electrode
   (2) wire, nickel electrode
   * (3) salt bridge, nickel electrode
   * (4) salt bridge, silver electrode



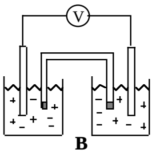
2. In an electrochemical cell, conduction through the electrolyte is due to:

   * (1) electrons moving through the solution attached to the ions
   * (2) electrons moving from ion to ion through the solution
   (3) the movement of both positive and negative ions
   (4) the movement of water molecules
   * (5) electrons moving across through the solution from one electrode to the other

3. The electrochemical cell shown below has 1.10 volts for its emf. There is an oxidation reaction and a reduction reaction.



Which one(s) of the diagrams below depict each half-cell as the reactions proceed? Note: In the following diagrams, cations are symbolized as + and anions as –. An electron is symbolized as e-.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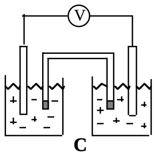
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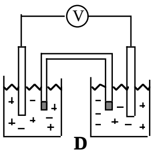
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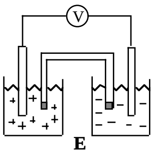
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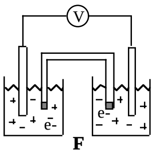
F

(1) Either C or D (2) E only (3) B only (4) Either B or E * (5) F only

Figure 1. Conceptual questions concerning the flow of electrons in solution.

The animations of the salt bridge included an overall animation that focused on the dynamics of the entire copper–zinc electrochemical cell, and a "close-up" of cation and anion migration out of the salt bridge (Fig. 2). The animation clearly shows only ions migrating in solution. This "close-up" view allows students to focus their attention on the critical concept being illustrated (*24*).

The computer animation of the electrolytic cell illustrates the plating of silver metal on an iron spoon (Fig. 3). The animation clearly shows electrons being released at the anode, bumping up from the anode through the wire and the battery to the cathode. Silver ions in solution migrate toward the iron cathode (spoon) where they capture electrons at the solution–metal interface, plating out on the electrode as silver metal. The animation clearly shows that only ions migrate in solution.

The distractors in each question were classified as being consistent (marked with an asterisk in Fig. 1) or inconsistent with the misconception that electrons flow in electrolyte solutions. Responses to the three conceptual questions were analyzed to determine whether students consistently demonstrated or failed to demonstrate this misconception. Of the 112 students who took the final exam, 3 (3%) consistently chose responses suggesting that electrons are present in solution, 40 (36%) consistently chose responses not suggesting that electrons exist in solution, and 69 (61%) chose responses inconsistent with regard to the presence of electrons in electrolyte solutions.

These results can be compared with those reported by Ogude and

Table 2. Animations Used in Electrochemistry Lectures

Animation	Focus	Duration
Zinc–copper electrochemical cell	Dynamics of entire cell: ion migration in electrolyte solutions and the salt bridge; movement of electrons in the wire; oxidation–reduction reactions at electrodes	45 s
Salt bridge (part I)	Cation and anion migration out of the salt bridge	30 s
Salt bridge (part II)	Cation and anion migration out of the salt bridge; charge balance in each half-cell	30 s
Electroplating silver onto iron	Electron movement in the wires; ion migration in the aqueous solution; oxidation process at anode; reduction process at cathode	45 s

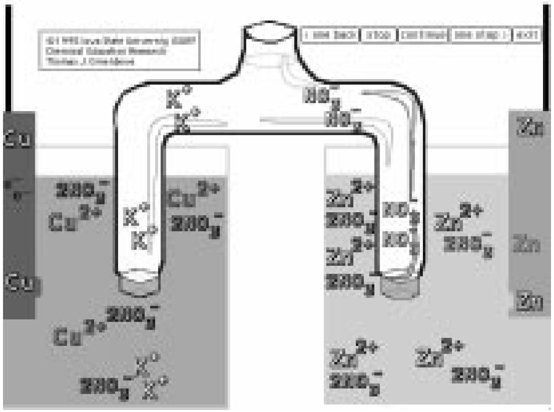

Figure 2. Close-up view of a representation of cation and anion migration in the salt bridge of a copper/zinc electrochemical cell.

Bradley (*8*), in which 40 first-year college students answered five conceptual questions concerning the flow of electrons in electrolyte solutions. In their study, 11 (28%) consistently demonstrated the misconception; 12 (30%) consistently did not demonstrate the misconception; and 17 (42%) were inconsistent. These numbers are complicated by the fact that Ogude and Bradley also used question #2 in Figure 1, but they included only response 5 as being consistent with the misconception; we included responses 1, 2, and 5 because all of them suggest that electrons exist in solution. Since 8 of the 40 students in Ogude and Bradley's study chose responses 1 and 2 for this question, it is likely that *more* than 28% consistently demonstrated and *less* than 30% consistently did not demonstrate this misconception.[3]

A chi-square test of independence was performed on the number of students in each study who consistently demonstrated or failed to demonstrate the misconception or were inconsistent in their responses. The results of this test ($\chi^2(2) = 21.90$, $p < .0001$) support the assumption that our teaching method had an effect on the proportion of students consistently demonstrating this misconception. Specifically, the test of independence suggests that the proportion of students in Ogude and Bradley's study who consistently demonstrated the misconception is larger than expected and the proportion of students in our study who consistently demonstrated the misconception is smaller than expected if the two groups were equivalent.

Our study suggests that active teaching to confront the misconception that electrons flow in electrolyte solutions and the salt bridge, using computer animations to help students visualize chemical reactions at the molecular level, decreased the proportion of students consistently demonstrating this misconception. The effect of viewing animations that focus attention on the molecular level (particulate nature of matter) can be seen in Williamson and Abraham's study (*20*), in which students who viewed animations based on the states of matter and reactions in solution were better able to visualize particulate behavior in chemical reactions.

Although the test of independence does not suggest a difference in the proportion of students inconsistently demonstrating the misconception, these numbers should be scrutinized. Since Ogude and Bradley's students answered five questions while ours answered only three, it is not unreasonable to expect a larger inconsistent group in their study due to random effects; however, our study shows a larger proportion of students who were inconsistent in their responses. Even though our students received instruction in electrochemistry that emphasized the correct model of current flow in electrolyte solutions and the salt bridge and were directed to readings about this topic in their textbook, previous experience suggests that this misconception resists change. Perhaps the computer animations shown in lecture were not shown long enough for students to process the information. Research is needed to determine whether these animations adequately explained the students' experiences and observations and appeared logical to the students (*25*).

Many of our students report that the computer animations are useful, but capturing the dynamic aspects of these processes on paper is difficult. They need more time to view the animations, make sense of them, and copy important information derived from them into their notes. To address these student concerns, we will place the computer animations used in lecture on our chemistry file server in the future. In this way, students will have access to the animations 24 hours a day and can review the animations and take notes at their leisure. Several animations are available on our World Wide Web site (*http://www.public.iastate.edu/~fipse-chem/homepage.html*). We will also prepare a lecture handout to reduce the time students spend copying the animations into their notes.

Perhaps viewing computer animations helps students build a better mental model (*26–27*) of electrochemical cells. Further research is needed to investigate this issue.

Summary

In a replication of Garnett and Treagust's interview study concerning electrochemical cells (*10*), we were able to confirm most of the misconceptions reported and to identify several new ones, including the notions that electrons can flow through aqueous solutions without assistance from the ions and that only anions constitute a flow of current in electrolyte solutions. Our students suggested two mechanisms for electron flow in electrolyte solutions and the salt bridge: electrons can either attach themselves to ions in solutions or they can flow by themselves without assistance from the ions. Analysis of the textbooks used by our students suggests a source of these misconceptions: obvious mistakes or misleading statements in the texts, which can be misinterpreted or over-generalized to inappropriate situations. We also demonstrated that instruction including the use of computer animations aimed at confronting the misconception that electrons flow in electrolyte solutions and the salt bridge can reduce the number of students who con-

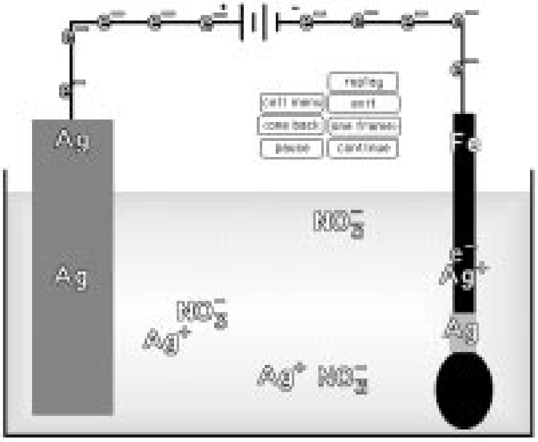

Figure 3. Computer screen image of the electrolytic plating of silver metal onto an iron spoon.

sistently demonstrate this misconception.

Acknowledgment

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Notes

1. Presented at the ACS National Meeting, Chicago, IL, August 20, 1995.

2. The numbering scheme for the misconceptions presented here is consistent with that used by Garnett and Treagust (*9, 10*) and Sanger and Greenbowe (*12*). Representative student quotes for each of these misconceptions were presented by the authors at the ACS National Meeting in Chicago in August 1995 (*13*).

3. If we reanalyze our data using only response 5 in question 2 as consistent with the misconception, our results change drastically: 1% of students consistently demonstrate the misconception, 58% consistently do not demonstrate it, and 41% are inconsistent in their responses.

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