HIDDEN PERSUADERS IN A SYSTEMIC APPROACH TO LEARNING ABOUT ELECTROCHEMICAL CELLS AND CIRCUITS

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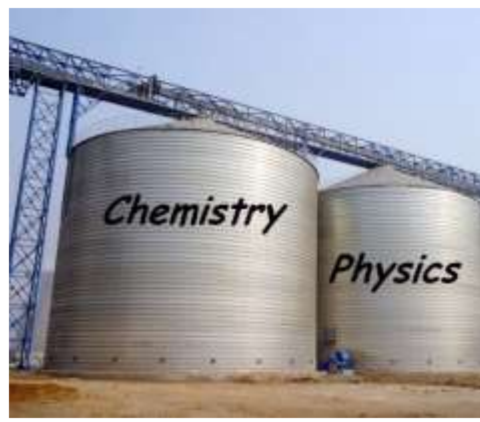
ABSTRACT

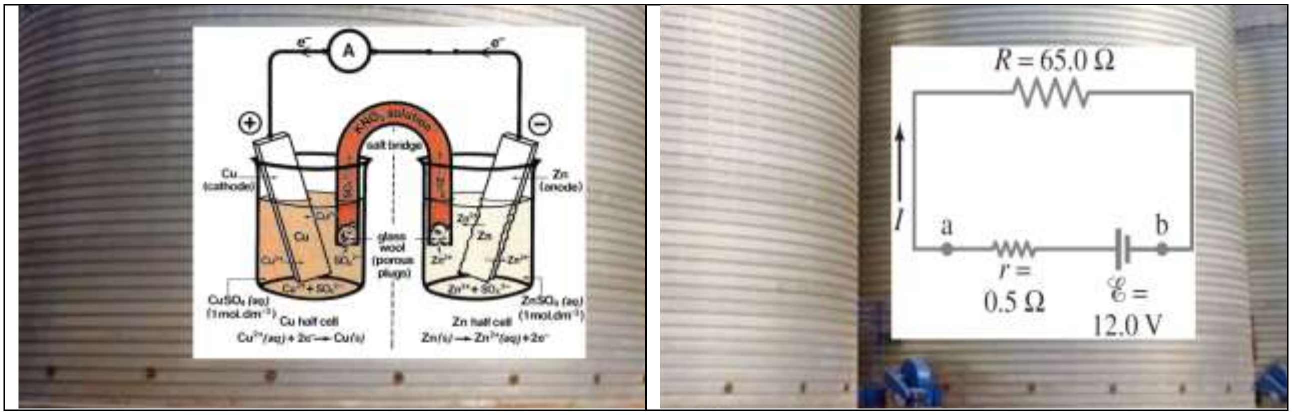
In this paper we discuss the meaning and language associated with use of the symbols + and - with particular reference to electrochemical cells and circuits. We propose that the undifferentiated use of plus and minus signs in that context creates possibilities for students to form misconceptions, and in this way the plus and minus signs are also "hidden persuaders". We consider in turn the charges of ions, the meaning of oxidation numbers, the role and character of electrodes, and the nature of standard electrode potentials. *[African Journal of Chemical Education—AJCE 13(1), January 2023]*

INTRODUCTION

A recent paper [1] in this Journal is testimony to the continuing concern about the teaching and learning of electrochemistry. It is evident that there are several aspects needing attention and some of these may originate in the traditional separate teaching about cells (in chemistry) and about circuits (in physics). In a previous paper [2] we argued that a systemic approach to teaching and learning about electrical cells and circuits could help avoid misconceptions separately reported by physics and chemistry education researchers. Our thinking is that to some extent this problem derives from the existence of two curricular silos of knowledge and the teaching and learning about them, when in reality there is one system.



In a subsequent presentation [3] we illustrated the problem with the images on the right and below. In the chemistry silo, students are presented with the chemist's depiction of the reactions in a voltaic cell. The current is shown as a flow of electrons going anticlockwise. In the physics silo, the students meet a very different depiction of a cell, merely two vertical lines with an unexplained space between them. They also see a separate resistor labelled r = 0.5 Ω that indicates the cell's internal resistance. The current is clockwise around the circuit.



Given the siloed curricula found in many educational institutions, it is perhaps not surprising that students do not see a circuit as a single physico-chemical system in which, as with all systems, a change in one part has effects in all the rest of the system. It is this latter idea that is a foundation concept for systems-thinking.

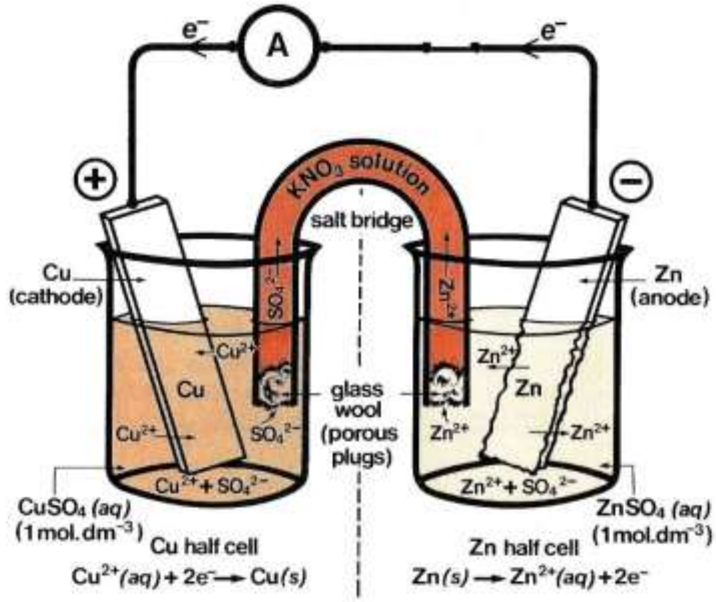
We have considered what a systemic approach to electric cells and circuits would look like in practice. As we developed the approach, the complexity of a development which involves some degree of integration of the teaching of two separate disciplines became increasingly apparent. Amongst the aspects of basic importance is that of the language used. Here the word 'language' is meant to cover terminology, symbols and models. Differences between the 'languages' of the disciplines are a potential source of misconceptions, especially when learners study both physics and chemistry as separate disciplines. We suggest that the idea of 'hidden persuaders' introduced by Schmidt (1991) offers an appropriate framework for thinking about science concepts in a situation where the topic of study lies within two disciplines. This is the situation when cells and circuits are studied as a system. When not treated as a system but as made up of two silos (physics and chemistry), there will be opportunity for forming misconceptions due to 'language' differences.

Schmidt (1991) [4] introduced the description 'hidden persuaders' to draw attention to some misconceptions about acid-base reactions that can be traced to the use of the term neutralisation. This term (or label as he called it) has a long history of use in association with describing the characteristics of acids and bases (or alkalis). In a subsequent paper, he and Volke (2003) [5] reported on the alternative concepts of students and the historical shift of meaning of the term oxidation. These examples from two traditional chemistry topics alert us to the likelihood of other areas of chemistry where other hidden persuaders lead to misconceptions

In this paper we discuss the meaning and language associated with use of the symbols + and - with particular reference to electrochemical cells and circuits. We propose that the undifferentiated use of plus and minus signs in that context creates possibilities for students to form misconceptions, and in this way the plus and minus signs are also "hidden persuaders". We consider in turn the charges of ions, the meaning of oxidation numbers, the role and character of electrodes, and the nature of standard electrode potentials.

We will begin by considering the diagram below; it and others like it are common in chemistry textbooks.

The diagram shows much sub-microscopic activity involving ions and electrons. The electrons are labelled with minus signs, the ions are labelled with plus or minus signs and the electrodes also have plus or minus signs next to them.



PLUS AND MINUS SYMBOLS AS HIDDEN PERSUADERS

In our previous paper [2] we listed 3 misconceptions each as reported from the two separate disciplines, one of which is the focus of this paper:

The + and – labels on the cell terminals represent the charges they bear. Inside the cell cations move towards the – electrode whilst anions move towards the + electrode. In electrolytic cells the signs are reversed.

It seems clear that the + and – labels on the cell terminals have been interpreted as indicators of charge in this quotation. We think that the + and – signs on electrodes, as used in cell diagrams, invite students to think in physics terms, by which they see charged ions being attracted to an oppositely-charged electrode. Garnett and Treagust [6] reported on how high school students tried to reason about ion movements inside a cell on the assumption that the anode had a negative charge and the cathode a positive charge. They were unsuccessful! We think this is probably another important example of what Schmidt described as a 'hidden persuader'.

CHARGES OF IONS

The + and - symbols are used to represent the charge of an entity such as an ion or an electron. Examples of the former are Cl^- and NH_4^+. (According to rules published by IUPAC [7a] the charge symbol is always placed in the upper-right position in the formula.) In polyatomic ions there may be indications of the principal atomic location of the charge, but otherwise the charge is assumed to 'belong' to all the atoms in an unspecified way. Multiple charges (multiples of the elementary charge) are catered for by use of numbers, as in SO_4^{2-} for example. These charges are recognised as a natural result of atoms being composed of protons and electrons (and neutrons). Ions with a negative charge are called anions whilst those with a positive charge are called cations.

In chemical equations where charged particles are represented, charge conservation must be observed, that is the nett charges represented on each side of the equation must be equal.

OXIDATION NUMBERS

In the dominant model of redox reactions, these reactions are viewed as electron transfer reactions. When the reactions involve ions, it is rather easy to see these transfers in the formulae of the reaction equation. But ions are not a necessary type of participant, and then identifying whether electron transfer is involved or not may be difficult. Oxidation numbers help for this purpose, because, in effect a polar covalent molecule is viewed as ionic. For example, the molecule H_2O is viewed as $2H^+O^{2-}$and therefore the formation of the water molecule from reaction between hydrogen and oxygen molecules (molecules which are not polar, and with pairs of equally-shared electrons) implies loss of electrons by H atoms and gain of electrons by O atoms and therefore a redox reaction. In the water molecule the oxidation number of H atoms is +I and of O atoms is –II. The use of Roman numbers like +I and –II emphasises that these are not full ionic charges when writing their formulae as H^{+I} and O^{-II}. The water molecules are not ionic, and they do not dissociate into ions in aqueous mixtures to any appreciable extent (K_w=10^{-14}mol^{2}dm^{-6}) and dissociation does not result in oxide ions but hydroxide ions.

ELECTRODES IN CELLS AND CIRCUITS

The electrodes of a cell are the key players in electrochemical phenomena. For example, ions generally form or react at electrodes as an essential part of the functioning of the cell when it is part of an electrical circuit. Chemical equations may also be written showing electrons (e^-) as reactants or products of the electrode reaction.

The electrodes are referred to as cathode or anode: at the cathode electrons from the external circuit are transferred to ions or molecules in the surrounding electrolyte; at the anode electrons are transferred to the external circuit either by loss of hydrated cations from the electrode or by loss of electrons from ions or molecules in the surrounding electrolyte. When the electrodes are connected by a conducting wire, electrons enter the external circuit at the anode and leave the external circuit at the cathode. Within the cell there is an oxidation half-reaction at the anode and a reduction half-reaction at the cathode. [7b]

Electrodes may also be shown with the + and – symbols and, in words, they may be referred to as positive and negative electrodes. The symbols frequently appear on cells used by the general public, and devices using the cells generally have a diagram directing the user which way round to place the ends of the cell with + and – symbols. Learners quite reasonably think the symbols may represent charges on the electrodes. These charges may then be invoked to explain ion migration inside the cell eg students may think that cations (having a + charge) move towards the electrode bearing a – sign. However, this is not correct: cations migrate towards the cathode, which is labelled with a + sign. More reasonable is explaining the observation that electrons (having a negative charge) in the external circuit move from the - electrode to the + electrode.

The truth is that the + and - electrode signs do not relate to an actual charge but to the model of conventional current in the external circuit. This is a current of positive charges, the opposite of reality as we now see it in a metallic conductor! Electrical circuit diagrams usually relate to this convention with the cell in a circuit often represented as:

+|l-

The left electrode is the source of the conventional positive current. In reality the left electrode is where electrons enter the cell to participate in the reduction half-reaction at the cathode.

In any case the whole process is driven by the potential difference between the two electrodes not by a charge difference between them: they do not have nett charges.

Unfortunately for many learners the + and - labels given to electrodes (as in the textbook example above) act as hidden persuaders of a misconception. They are easily misunderstood as nett charges, because electrochemical cell diagrams usually have many + and – signs scattered around and most of the time they do mean to describe charges. The only exception is the signs on the electrodes. These signs should be omitted from electrochemical cell diagrams when the diagrams support understanding of events inside the cell. But of course, the circuit cannot be ignored, and it is the conduit for electron transfer between the electrodes. However, teachers of the topic should refrain from including these hidden persuaders with the electrodes, until a focus on the external circuit is appropriate. From the viewpoint of the cell, the electrodes have names (cathode and anode) which can be linked with reduction and oxidation half-reactions respectively and with the ion movements in the electrolyte.

STANDARD ELECTRODE POTENTIALS

Although electrodes may have electric potentials these cannot be measured: two electrodes are required to make a cell. The cell has a potential difference between the two electrodes which can be measured with a voltmeter. It is the sum of an oxidation potential (E_{ox}) for the anode and a reduction potential (E_{red}) for the cathode, and is generally called the cell potential (E_{cell}). A standard reference electrode (the standard hydrogen electrode (SHE)) has been assigned the potential of 0,00 V and the potentials of all other electrodes are measured as components of a cell in which one half is the SHE. Tables of these electrode potentials are normally given as standard reduction potentials, and some appear with positive values and some with negative values. Positive values identify reduction half-reactions that are energetically more favourable than reduction of hydrogen ions, whilst negative values imply reduction is less favourable than is the reduction of hydrogen ions.

Although reduction potentials may be listed, oxidation potentials may be derived easily since $E_{red} = -E_{ox}$.

The + and – signs of electrode potentials reflect the use of a zero of reference in comparing all the different possible electrodes. (The situation is analogous to the Celsius temperature scale.) In chemistry education such comparisons are important for linking with Periodic Table trends.

Although the reason why some standard reduction potentials are positive and some are negative is straightforward, we found that some student teachers were persuaded to explain them in terms of charges, for example, as:

> *'Anode is a negative electrode, meaning the most negative species from standard reduction potentials will be anode….Cathode is a positive electrode which is mostly positive species from standard reduction potentials.'*

SYSTEMS-THINKING ABOUT CELLS AND CIRCUITS

The above remarks focus on the chemistry inside the cell, with superficial reference to the external circuit. An interdisciplinary approach to cells and circuits will recognise the physics concerns with the effect of internal resistance and its increase as more current is drawn from the cell as the resistance in the external circuit decreases. This effect is taught in physics classes but seldom explained in terms of the reactions and ion movement inside the cell. An interdisciplinary approach that includes the chemistry discussed above would enable a teacher to give a satisfactory explanation for the internal resistance effect, the heating of the cell as it produces current, the relationship between the maximum current and the physical size of the cell, the choice of materials in the cell, and the reasons for connecting cells in series or in parallel in batteries

We would argue that the teaching strategy employed needs to take into account hidden persuaders that originate in one discipline and may be a source of misunderstanding in another. Learning about systems-thinking needs to include provision for confronting this issue. In the context of Big Ideas *about* science [8] there are likely to be many instances which relate to:

‘Scientific explanations, theories and models are those that best fit the facts known at a particular time.’

We argue that the cells and circuits case brings to the surface a problem that has been acknowledged but not satisfactorily confronted. In the current South African national curriculum

(CAPS) [9] for example, there is advice for grade 10 teachers of the Electricity and Magnetism knowledge area regarding conventional current:

'The direction of current in a circuit is from the positive end of the battery, through the circuit and back to the negative end of the battery. In the past, this was called conventional current to distinguish it from the electron flow. However, it is sufficient to call it the direction of the current and just mention that this is by convention.'

This advice is surely unhelpful after teaching in earlier grades has devoted time to describing the electron flow in an electric circuit and the energy transfer associated with this. It also does not prepare for the teaching about electrochemical cells in grade 12.

Equally concerning is the implicit encouragement to thinking that the cell has charges on its terminals. Use of the terms 'positive' and 'negative' should be avoided as they may strengthen the persuasive influence towards belief in charges on the terminals. The + and – signs may be referred to as "plus and minus" signs instead, a reference which may have less persuasive potential to lead to misconception. Teachers could use "plus" and "minus" simply as indicators of the correct way to install or connect a battery. A teacher might say "The red wire goes to the terminal with the plus sign and the black wire goes to the terminal with the minus sign".

It is better rather to heed the conclusion (30 years ago!) of Garnett and Treagust [10]:

"teachers, curriculum developers, and textbook writers, if they are to minimize potential misconceptions, need to be cognizant of the relationship between physics and chemistry teaching…"

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