A SYSTEMIC APPROACH TO TEACHING AND LEARNING ABOUT ELECTRICAL CELLS AND CIRCUITS USING TWO BIG IDEAS OF SCIENCE

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ABSTRACT

Our recent exploration of the ideas of student-teachers about DC electric circuits and electrochemical cells has shown the prevalence of numerous misconceptions previously reported in the physics education and chemistry education literature. Our students have developed their concepts throughout the period from grade 6 to BEd III in two separate streams – one essentially in chemistry and the other in physics – despite the reality that a cell and circuit together constitute a system. The potential benefits of adopting a Systemic Approach supported by two Big Ideas of Science Education in addressing the needs of our future science teachers are explored. A joint physics-chemistry topic devoted to the cell and circuit system in the BEd curriculum is proposed. *[African Journal of Chemical Education—AJCE 11(1), January 2021]*

BIG IDEAS AND THE SYSTEMIC APPROACH TO TEACHING AND LEARNING SCIENCE

In a previous paper (Bradley and Moodie, 2017) [1] we argued that the potential link between the Systemic Approach to teaching and learning chemistry (Fahmy and Lagowski, 1999) [2] and the Big Ideas of Science Education (Harlen, 2010) [3] deserved to be explored. Using one strand (Matter and Materials) of the South African Natural Sciences curriculum (grade 7) as an example, we showed how content specifications in the national curriculum could readily serve to build awareness and comprehension of one Big Idea. The Big Idea chosen was the one about particles:

"All matter in the Universe is made of very small particles"

We have concluded [4] that the Systemic Approach provides an over-arching teaching and learning idea that, in conjunction with the Big Idea construct, could help:

(a) create stronger coherence in an existing national curriculum,
(b) strengthen its role as preparation for further study,
(c) establish a more useful framework of understanding for future citizens,
(d) develop systems-thinking.

More recently we have investigated an important component of another strand in the Natural Sciences curriculum, namely Energy and Change, starting with a study of the conceptions held by student teachers at our university (Bradley, Khulu, Moodie and Mphahlele, 2019a) [5]. The focus of our study was that of cells and DC circuits, a topic introduced in the Natural Sciences curriculum in grades 6 to 9. (The topic is taught further in grades 10-12 in the school subject Physical Sciences.) The outcomes were disappointing in the sense that student teachers of Physical Science in a third year physics class for the BEd held many misconceptions about cells and DC circuits. The physics education literature is replete with reports of such problems for school learners and their teachers, as well as for student-teachers, so we were not greatly surprised. The chemistry education literature regarding student conceptions of electrochemical cells is also extensive, and a subsequent study of our fourth year BEd students in a chemistry class, showed again that they held many of the previously reported misconceptions.

Although we use the phrase cells and DC circuits, it is important to note that in a sense DC circuits are traditionally viewed as a physics topic whilst cells (electrochemical cells) are viewed as a chemistry topic. The curricular overlap of the two is very limited, despite the fact that DC circuits (in physics) necessarily include a cell and electrochemical cells (in chemistry) necessarily include an 'external circuit'. This very limited extent of overlap exists within both the school subjects Natural Sciences (grades 4-9) and Physical Sciences (grades 10-12), and it continues in our current BEd curriculum. Yet any electrical circuit is clearly one system (Härtel, 1982) [6], and so teaching about this system as two separate domains might well be expected to run into difficulties, unless substantial efforts are made to bridge the two especially in the earlier stages of science education.

In this paper we explore the need for a Systemic Approach to the teaching and learning of cells and circuits, as a way of helping student-teachers overcome the burden of misconceptions they bring from school. This approach would best be implemented as a formal topic within the BEd curriculum for student teachers of Natural Sciences and Physical Sciences. We envisage an important role for two Big Ideas within this approach, namely the 'particle Big Idea' cited above, and the Big Idea concerning energy, namely:

"The total amount of energy in the Universe is always the same but can be transferred from one energy store to another during an event." [7]

Our hope is that room can be made to accommodate such a topic in the BEd curriculum, even though the physics and chemistry teaching are currently separate and in sequence.

SOME DIFFICULTIES IN UNDERSTANDING CELLS AND CIRCUITS REVEALED BY STUDIES OF MISCONCEPTIONS

The development of our approach consciously aims to take into account the extensive research into student misconceptions. The literature regarding misconceptions comes both from physics education and chemistry education research. A selection of these follows:

P. From physics education research [8], [9], [10]:

(i) The current is consumed by components in the circuit; the cell is like a tank that stores current until it runs empty.

(ii) The current/electricity is consumed, and it is thus attenuated at each resistor in sequence, so that very little returns to the cell.

(iii) The current is the cause of the potential difference across a resistor. If there is no current through a part of the circuit, then the PD across that part is zero.

C. From chemistry education research [11], [12], [13]:

(i) Electrons flow not only through the electric circuit but through the cell itself.

(ii) The cell stores electric current and releases it when the circuit is completed.

(iii) 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.

Reflecting upon these lists it should first be noted that they also are divided into two. We are not aware of published reports bringing the two together in order to draw inferences about the system of cells and circuits. Secondly, it should be noted that these are widespread misconceptions held by substantial fractions of students and teachers according to the reports. We are therefore looking at a substantial problem in science teaching that student teachers (as in our BEd courses) need to overcome. 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.

Taking into account the World-wide curricular separation of cells and circuits, we felt the need to describe in the following sections some of the specific features of a topic curriculum for student-teachers, which is designed to bring coherence and understanding to cells and circuits.

TOWARDS A TOPIC FOR STUDENT-TEACHERS ABOUT CELLS AND CIRCUITS

1. Finding a Starting Point: The Cell as a Source of Energy

Faced by all the misconceptions and the aim to address them effectively in the context of our BEd curriculum, we thought to go back to 'the beginning' (Bradley, Khulu, Moodie and Mphahlele, 2019b) [14]. By this we mean, where did cells and circuits start? This is quite clear; it goes back to Volta and his discovery of current electricity arising from a 'pile' – that is pieces of different metals interleaved by moist, salty paper – which he reported in 1800 approximately. At that point in time there could have been little doubt that the 'cell' (represented by the two different metal pieces and salty interface) caused the current. However, it was a matter for speculation as to what flowed in the 'external circuit'.

It was also evident that the 'cell' was a source of energy. Apart from what Volta himself observed, a very striking, different illustration of the cell as a source of energy came swiftly: the electrolysis of water. The decomposition of water, with two different products appearing at the two electrodes, had far-reaching implications for the understanding of the nature of substances.

These discoveries were reported at much the same time as Dalton re-launched the Atomic Theory, giving huge impetus to establishing the 'particle Big Idea'.

Identifying the cell as a source of energy is easy to say and acknowledge as an observed event. But the question is, how does it work? Traditional physics teaching about DC circuits almost always avoids answering this question. Most rely on the 'source of energy' mantra, and then focus on current and the continuity of the electric circuit. Some models of DC circuits even propagate the erroneous idea that the electronic current is continuous through the cell and the circuit [15] [16]. Some authors who have advocated a priority attention on 'voltage' rather than current (Psillos et al, 1988) [17] in teaching about circuits, have found themselves challenged by thoughtful students as to what is happening in the cell. Regrettably the crucial understanding that the cell voltage (or emf) directly reflects the energy change of the cell reaction on a per coulomb basis is not often clear. The little silo that is DC circuits, nurtures its own culture, with the links to more general science concepts weakly evident. It may be correctly said that the cell is a source of energy, but it would be more meaningful to say that the cell chemical reaction is a source of energy.

2. Sources of Energy and How They transfer Energy

There are other sources of energy in everyday experience: most notably we have combustion of fuels. These do not look to have anything in common with a cell at work. However, in commercial cells of today, we see the ingredients of a chemical reaction. Volta and other scientists of his time, were well aware of chemical reactions as energy sources, but would not have been able to explain what happens in ways we could understand today.

In today's language we could describe the combustion of fuels, as a reaction between the fuel and oxygen, usually forming carbon dioxide and water. The reaction is described as exothermic, meaning energy is released from the reaction mixture, as reactants form products. The energy is transferred to the surroundings mostly by molecular collisions. (High KE product molecules collide with lower KE molecules in the surroundings.) We do not see this spectacle (fire, flames, explosions) when the cell transfers energy in a circuit. Indeed, transfer of energy by the cell is not by molecule-molecule collisions in the circuit but by electron-molecule collisions.

3. Why is Combustion of Fuels a Source of Energy?

Many (even most) chemical reactions are exothermic, but some are more exothermic than others. Amongst those with high exothermicity, it is the oxidation-reduction (redox) variety that are noteworthy. These are reactions in which electrons are transferred between reactant molecules. Oxygen is an element with atoms that have a relatively strong attraction for electrons (ie high electronegativity) – indeed the electronegativity of O atoms is second highest in a list of the atoms of more than 100 elements. Electrons associated with other atoms have a higher energy than those in O atoms; when these move to (or even towards) O atoms they decrease in energy and energy is transferred to other atoms and molecules. It is this electron transfer from one atom (of low electronegativity) to another (of high electronegativity (eg O) that is the origin of the exothermicity of combustions and makes them sources of energy.

[It should be noted that to state that fuels are a source of energy is wrong; it is their combustion which is.]

4. Cells as a Source of Energy

Cells have the ingredients of a redox reaction in them. In the fuel cells that increasingly appear in our daily lives, combustion of fuels is the type of reaction used. The fuel is often hydrogen, the combustion of which produces water, a product with no pollution problems! But in the ordinary cells that are used in classroom DC circuits and in countless consumer appliances, the reactants are not so simply related to the familiar fuel combustion.

Looking first at the hydrogen-based fuel cell, the reaction is:

$$2\ H_2(g)\ +\ O_2(g)\ =\ 2\ H_2O\ (g)$$

It is evident in this equation that the original bonds are non-polar because the atoms in these molecules are identical: H – H and O=O (or H:H and O::O)

By contrast in the water molecules they are not: H-O-H (or H:O:H)

and in these molecules the O atom draws the shared electrons of the bonds away from the H atoms towards itself.

In the very common 1,5 V cell, the reactants are more complicated:

$$Zn(s)\ +\ MnO_2(s)\ +\ H_2O(l)\ =\ ZnO(s)\ +\ Mn(OH)_2(s)$$

But one can spot the change of Zn to ZnO very easily as the equivalent of the H_2 going to H_2O in the fuel cell. The MnO_2 may be visualised as the source of the O atom.

5. How Can Electron Transfer Take place Through an External Circuit?

In a typical cell, one reactant is located around one electrode, spatially separate from the other reactant located around the other electrode. With a metal wire (electronic conductor) connecting the two terminals, electrons may be transferred from the one reactant to the other. There is a flow of electrons from the terminal with the – sign to the terminal with the + sign. This electron flow is the current (or electric current). It takes place because the electrons decrease in potential energy as they go from the one reactant at the – electrode to the other reactant at the + electrode. The current is caused by this PE difference, not the other way around. Electrons are not lost in the process but they do experience collisions with atoms in the wire as they move through it. These collisions result in energy transfer from the electrons.

This process cannot be sustained without a mechanism inside the cell for restoring charge balance. Loss of electrons from the – electrode leaves positive charges at that electrode. Gain of electrons at the + electrode results in negative charges at the + electrode. Further transfers of electrons are increasingly inhibited by these charges. Inside the cell therefore provision is made for positive ions to diffuse away from the – electrode and for negative ions to move away from the + electrode. This ion movement is intrinsically slower than the electron movement in the circuit, and if the current in the circuit is too large (flow of electrons too fast) then the internal resistance of the cell will increasingly limit the current.

6. How the Source of Energy is Quantitatively Described

When describing the energy changes in chemical reactions, this is commonly done in units of kJ/mol. Whilst this is in principle possible to do when the reaction takes place inside a cell, this is not common practice. Instead the energy characteristic of the cell is described using the unit Volt. This is equivalent to J/C. This is the energy change per coulomb of charge transferred. Each electron bears a charge of 1,6 x 10^{-19} C, so I,5 V corresponds approximately to 145 kJ/mol of electrons. For consumers, this equivalence is just a distraction, but for science teachers it can help bridge the gap between physics and chemistry.

The implicit message about cells of different sizes, all of which are labelled 1,5 V, is that they all deliver the same energy per coulomb but the bigger the size of the cell the more is the total energy available. Also when a 9 V battery is considered, this is a battery of six 1,5 V cells in series. (Correct usage of the descriptors cell and battery is important in avoiding wrong messages being received!) As a consumer it is surprising that when buying a cell, you do not have a direct statement of how much energy you are getting for your money. Nor, if you compare cells of different sizes, whether it is better to buy a big one rather than a number of small ones. (Of course the device for which you are making your purchase determines the size you must buy.)

RE-VISITING SOME OF THE MISCONCEPTIONS REPORTED IN THE PHYSICS AND CHEMISTRY EDUCATION LITERATURE

Let us be direct and address each misconception in the light of the above paragraphs.

P (i) A current is a flow of something. Air and water are early experiences of what 'current' means. A current of electricity is no different in that it is a flow of charges. Current does not flow; it is the flow. Hence it cannot be stored and it cannot be consumed. Flow rate can be altered. A cell stores chemical reactants and as long as they remain there can be a current when the cell is connected to a circuit.

P (ii) Components in a circuit affect the current; it may be relatively large or small. But it is not consumed or lost; it is a flow of electrons being transferred from one terminal to the other as the cell reaction happens. No electrons are lost.

P (iii) There is a potential difference between the cell terminals. The origin of this is the energy change of the chemical reaction that will take place inside the cell when the terminals are connected with an electronic conductor. The term electromotive force is less helpful than the recognition that the cell 'voltage' is joules of energy per coulomb of charge transferred. The current is not the cause of the voltage; it is the obverse.

C (i) Electrons are transferred between reactants via the circuit external to the cell. The electrons concerned decrease in PE and they will not spontaneously go back to where they started from. Nevertheless, their transfer has created a charge imbalance inside the cell between the two electrode regions. Ion movement (anions towards the anode, cations towards the cathode) takes place towards the re-establishment of charge balance.

C (ii) There is no chemical reaction inside the cell without electronic connection of the terminals. The flow of electrons that occurs when the terminals are connected is an electric current. In any case a current cannot be stored; it is a flow.

C (iii) The signage associated with cells is problematic for obvious reasons: in our minds a + sign is often directly linked with a + charge, and similarly a – sign with a negative charge. Explaining the functioning of electrochemical cells often invokes this linkage erroneously. There are no charges on the terminals. The – sign on a cell casing indicates the terminal from which electrons will enter the circuit, whilst a + sign indicates the terminal at which electrons will enter the cell. Inside the cell, ion migration occurs as described in C (i) but this is to restore charge balance in the electrolyte not because there is a negative charge or positive charge associated with the respective electrodes.

Explaining electrolytic cells embodies many of the same ideas as those involved with voltaic (galvanic) cells. However of course the chemical reaction inside the cell is not a source of energy; it absorbs energy (or it is not exothermic, but endothermic). Hence it is driven by an external source of energy. Nevertheless, apart from this, similar concepts arise. There is no electron migration inside the cell. Electron transfers occur at each electrode. Electrons enter the cell at the + electrode (and reduction occurs); electrons leave the cell at the – electrode (where oxidation occurs), and these symbols do not imply the respective charges on the electrodes.

A SYSTEMIC APPROACH TO TEACHING AND LEARNING ABOUT CELLS AND CIRCUITS

Around the World most science curricula are structured to develop knowledge and understanding of cells and circuits through two separate streams. In SA the story opens in grade 7 in the strand Energy and Change and it is continued to grade 9 in this strand. The cell is identified as a store of energy and a source of energy, and current in the circuit is defined as a flow of charges. The basic effects of current flow are exemplified as heating, lighting and electrolysis. Although it is acknowledged that there is a chemical reaction inside the cell there is essentially no explanation of how it works. This is inevitable because of the lack of development of chemical reaction concepts. Concepts of chemical reactions are developed in the Matter and Materials strand but energy is not even mentioned in the curriculum description for that strand. Atomic structure is included in this strand whilst electrons are associated with electric current in the Energy and Change strand. But the terms oxidation and reduction are not mentioned anywhere, even though reactions between elements and oxygen is a grade 9 topic.

In these circumstances introducing a Systemic Approach to teaching about cells and circuits in the school Natural Sciences curriculum (grade 4-9) is problematic for teachers. At present, and for the forseeable future, school learners who choose not to study Physical Science in grades 10-12, probably leave school with no understanding of how the cells, which they will use for much of their life, function. School learners who do choose to study Physical Science are unlikely to have much better understanding because electrochemical cells belong to the chemistry half of the curriculum, and circuits belong to the physics half of the curriculum, and the overlap of the two is zero (unless an initiative is taken by individual teachers).

This lends further weight to the need to address the legacy of consequences in the BEd curriculum, using the Systemic Approach and Big Ideas outlined above. Our student-teachers will hopefully be some of the individual teachers who take the initiative. We also hope that existing science teachers may be tempted by an in-service Short Course with a similar curriculum.

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