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Chapter 10
Shared Perspectives from Two Universities on Teaching Electricity: Lessons for Science Teacher Education

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Hardly any other discovery has had such a lasting impact on modern civilization as the discovery of electricity. The teaching of electricity is therefore not only part of science curricula in South Africa and Germany, but also throughout the world. However, it is acknowledged in schools and universities worldwide that the topic represents a great challenge to students and teachers alike. Although there is an abundance of educational research on students' difficulties with DC circuits and electrochemical cells, this research has rarely been brought together. In this chapter, we shall focus on the question of whether considering these two bodies of work together can give us new insights, and suggest new approaches for designing science teacher education at university.

As DC circuits have traditionally been a physics topic and electrochemical cells a chemistry topic, many educational institutions and policy makers maintain a silo mentality. Even when the teaching subject is physical science (as in South Africa), rather than physics and chemistry (as in Germany), teaching does not, in general, succeed in helping students understand how cells and circuits constitute an electrical system. In this chapter, we will first provide an overview of the science teacher preparation programs at the University of Tübingen and the University of the Witwatersrand. We proceed by looking more closely at the physics and chemistry of electric circuits, before providing an analysis of students' typical conceptual difficulties with cells and circuits. Drawing on our experiences in the two contexts, Wits and Tübingen, we discuss possible pedagogical implications for science teachers-in-training. In particular, we propose that teacher education about electricity should over-

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come the silo mentality and emphasize that cells and circuits constitute an electrical system, focus more on the concept of voltage by examining how voltage is created and maintained by cells, and provide students with powerful models and analogies that help visualize potential differences in circuits.

1 Introduction

Ever since, some two centuries ago, Volta constructed his "pile" and observed current electricity, the world has been changed by the consequences, and is still being changed. Explaining the pile's working and the phenomenon of current electricity took many years of research and required the parallel development of the atomic theory, which was re-launched by Dalton. Today, cells and circuits are standard topics in school curricula around the world, and science teachers try to explain them at a suitable level. Likewise, the preparation of new science teachers necessarily pays attention to these topics and how best to teach them.

These educational tasks have proved difficult. There is abundant evidence around the world that science teachers and their students often do not fully understand the phenomena involved (Burde, 2018; Duit, 2009; McDermott & Shaffer, 1992; Pardhan & Bano, 2001). There are numerous reasons for these conceptual difficulties, ranging from an unnecessary focus on current rather than voltage (Cohen et al., 1983), to the fact that the physical processes in circuits are generally hard to imagine, as they elude direct perception (Burde & Wilhelm, 2017). In addition to the abstract nature of electric circuits, the conceptual difficulties involved in voltage, as well as cells and their role in circuits, may also be attributed to the fact that DC circuits are traditionally a physics topic and electrochemical cells a chemistry topic.

These problems are known in both our institutions. Research efforts have been conducted to overcome them. The approaches have been somewhat different in emphasis, which can be attributed to the different school and teacher education curricula followed in the two countries. While research at Wits aims to help students understand the interaction between the physics and chemistry components in circuits, research at Tübingen primarily focusses on approaches that provide students with a better understanding of voltage.

In this chapter of the book "Teacher Education in South Africa and Germany. Shared Perspectives", we shall briefly compare the science teacher education curricula at our two universities, give a brief introduction to the physics and chemistry of electric circuits, and describe students' conceptual difficulties with cells and circuits. Based on these considerations, we bring together educational research on cells and circuits, which has rarely been done before. In particular, we propose that teacher education about electricity should focus more on the concept of voltage, e.g., by looking more closely at how voltage is created and maintained by cells. Teaching should emphasize that cells and circuits constitute an electrical system. Furthermore, we suggest that prospective teachers be aware of typical misconceptions (sometimes called "alternative conceptions"), as well as effective models and analogies that take these learning difficulties into account, in order to help students develop a better qualitative understanding of circuits.

2 Science teacher preparation

2.1 At the University of the Witwatersrand (Wits)

Wits University is a medium-sized, urban university with faculties of science, engineering and health sciences. However, these faculties play no part in the preparation of science teachers, since all school-teacher preparation (content and methodology) falls under the School of Education within the Faculty of Humanities. Furthermore, the School of Education is located on a campus separate from those housing the other faculties mentioned. The result of this physical and administrative arrangement is that there is little contact between the staff teaching future science teachers and the staff of other faculties with cognate subject interests.

The following remarks provide context for understanding the 4-year Bachelor of Education curriculum followed by student science teachers. In the first two years, the science content and method courses relate strongly to the grade 4–9 Natural Sciences school curriculum, even if a student intends to teach grade 10–12 Physical Sciences or Life Sciences. It is only in the 3rd and 4th years that students aiming at the latter qualification engage with the grade 10–12 subject content and method. Little time is left for developing in-depth knowledge of the school science content in these circumstances.

The national school curriculum offers Physical Sciences as a subject for grades 10–12, but the subjects physics and chemistry are not offered separately. The subject matter content of the Physical Sciences curriculum is quite distinctly divided into a physics and a chemistry component, and the final matriculation exam comprises two papers: one devoted to physics and one to chemistry. The same kind of separation is maintained in the Physical Sciences content courses in the 3rd and 4th year of the B. Ed.

curriculum. This, of course, is consistent with the B. Ed.'s strong emphasis on preparing students to teach the existing school subject.
The Wits authors' current research is in promoting the interaction between the physics and chemistry components of the Physical Sciences courses in the B. Ed. curriculum. Cells and circuits are the primary topics in this research (Bradley et al., 2019a, 2019b).

2.2 At the University of Tübingen

Tübingen University, founded in 1477, is not only one of the oldest, but also one of the strongest research universities in Germany. With more than 27,000 enrolled students, it is a mid-sized university and is located in the state of Baden-Württemberg, in the south-west of Germany. Teacher education is organized by the Tübingen School of Education (TüSE), which coordinates the different programs of study across the faculties of the university. While prospective primary school teachers (for grade 1 to 4) and prospective lower secondary school teachers (grade 5 to 10) receive their training at specialized Universities of Education in the state of Baden-Württemberg, teacher training at Tübingen University is aimed at prospective Gymnasium teachers intending to teach grade 5 to 13. In Tübingen, students complete a course tailored specifically to the needs of prospective teachers, leading to a Bachelor of Education (B. Ed.) or Master of Education (M. Ed.). Since the natural sciences at most German schools are usually not taught in the form of an integrated subject “science”, but as separate subjects like chemistry, biology, and physics (KMK, 2020), teacher training at the University of Tübingen is also subject-specific.
As a result, future physics teachers mostly attend the same physics lectures and seminars organized by the Department of Physics as their peers studying for a Bachelor of Science (B. Sc.). As part of their course, future teachers not only specialize in two subjects (e.g., physics and mathematics) to develop their content knowledge (CK), but also attend seminars that are specifically designed to advance their pedagogical knowledge (PK) as well as their pedagogical content knowledge (PCK) (TüSE, 2019). In Tübingen, lectures and seminars aimed at increasing students' content knowledge (CK) are held by lecturers of the respective departments, e.g., the Department of Physics. Consequently, students at Tübingen University receive a well-founded education in physics that goes beyond the typical school content, but may not necessarily have a strong understanding of chemistry, as many teaching students in Tübingen have math as their second subject. This difference between the two teacher education curricula also reflects the differences between the school systems in Germany and South Africa. In the semi-

nars designed to enhance the prospective physics teachers' PCK, organized by the Physics Education Research Group, one area of focus lies in familiarizing future physics teachers with typical misconceptions, e.g., in the fields of mechanics, optics and electricity, and in discussing effective, research-based approaches to help secondary school students develop an adequate conceptual understanding, e.g., of electric circuits.

2.3 Research in electricity concepts in the two curricular contexts

The different curricular contexts in which the authors of this chapter teach naturally have an influence on the research that attracts their attention. Given that no integrated subject "science" exists at the University of Tübingen, as physics and chemistry are taught here as separate subjects, its research primarily focusses on how to provide students with a better conceptual understanding of the physics of, for example, DC circuits. In this case, research projects in Tübingen focus on identifying students' misconceptions about DC circuits, ways to foster a better conceptual understanding of voltage, as well as effective models and analogies to better illustrate key aspects of simple DC circuits.

In the Wits context, the 3rd and 4th year courses are titled Physical Science, and equal time in each year is given to physics and chemistry topics. Furthermore, following the secondary school curriculum structure, the physics and chemistry topics in the B. Ed. at Wits are presented almost entirely as separate topics: the chemistry topic of electrochemical cells and the physics topic of DC circuits. The research focus here is on the understanding of cell chemistry that can result in understanding these circuits better.

In sections 3, 4 and 5 of this chapter, separate sub-sections are devoted to chemistry and physics issues in understanding what is, in fact, one physico-chemical system. These sub-sections come from Wits and Tübingen respectively, and reflect the different research interests of the two institutions.

3 The physics and chemistry of electric circuits

Before discussing students' conceptual difficulties with cells and circuits, e.g., with regard to current and voltage, it is important to first give a brief introduction to the physics and chemistry of electric circuits. The following sections will therefore explain the role of potential difference in circuits and briefly describe how a cell works from a chemical perspective.

3.1 What happens inside a cell?

A short answer is: there is a chemical reaction. Chemical reactions usually involve two reactants. The reaction occurs when the different reactant molecules collide with sufficient vigor. As the reaction takes place, there is an energy change: usually the products have a lower potential energy than the reactant molecules and energy is transferred to the surroundings. Such reactions are called exothermic. This energy change (usually measured in kJ / mol) may be said to be the driving force of the reaction (neglecting entropy for simplicity). One class of reaction involves electron transfer between the different molecules. These are called redox reactions. It is only this class of reaction that can be used in an electrochemical cell.

In the cell, the reactants are kept separate from one another. One reactant is concentrated around one terminal and the other reactant is concentrated around the other terminal. The reactant that is the source of electrons is located around the – terminal, while the reactant that receives electrons is located around the + terminal. The outer casing of commercial cells always shows – and + signs at the corresponding terminals. When the two terminals are connected by a metal wire, which is a conductor of electrons, electron transfer can take place. We say there is an electric current in the conductor; this may be described as a flow of electrons. In this context, the driving force originating in the cell is described as the emf (electromotive force) and is measured in volts (J / C). Commercial cells usually have this quantity shown on the outer casing (e.g., 1.5 V). The casing does not show the current because it depends on the circuit in which the cell is incorporated. The current reflects the rate of the chemical reaction inside the cell, so the rate varies with the circuit.

Inside the cell, there are additional changes. The electron transfer results in positive charges accumulating inside the cell around the – terminal and negative charges accumulating around the + terminal. Movement of positive ions away from the – terminal and negative ions away from the + terminal takes place to maintain a uniform distribution of positive and negative charges in the cell electrolyte. This two-way ion movement forms part of the continuity of current through the system in operation, the electronic transfer external to the cell being the more obvious part of this.

3.2 What is the role of voltage in circuits?

When hearing the term “electric circuit”, most people think of electric current, which is often associated with the mental picture of a flowing river. Even if this association is not wrong, there is another physical quantity that is at least as important as the electric current: voltage. However, in contrast to current, most people lack a qualitative understanding of voltage (Burde, 2018; McDermott & Shaffer, 1992; Rhöneck, 1986). This is problematic for at least two reasons: firstly, voltage plays a more important role in everyday life than current. Every child learns that high voltage is dangerous and that you should never stick your fingers into an electric socket, as it works with a voltage of 230 V. In addition, voltage specifications can be found on everyday objects, e.g., cells marked as 1.5 V. Thirdly, voltage also plays a central role from a physical point of view, since there is only a current through an electric device if a voltage – created and maintained by the chemical reaction in the cell – is applied to it. This raises the question of what voltage is and what role it plays in electric circuits.

As described at the beginning, batteries maintain a constant voltage between their two terminals. This simple statement contains two important aspects: firstly, that batteries are not a source of a constant current, but of a constant voltage; and secondly, that voltage is a physical quantity that only occurs between two distinct points, in this case between the two terminals of a battery. Without going into too much detail, this example already shows that voltage is a differential quantity, therefore the voltage V_{AB} between point A and point B is defined as the potential difference between the electric potential at point A and B, in this case between the terminals of the battery:

$$V_{AB} = \Phi_B - \Phi_A$$

V_{AB}: Voltage between point A and B
Φ_A: Electric potential at point A
Φ_B: Electric potential at point B

If a wire is attached to each battery terminal, the electric potential in each wire is the same as at its battery pole. In an open circuit, this means that the potential difference between the unconnected ends of the two wires is the same as the potential difference between the two battery terminals. If these two previously unconnected wires are attached to a light bulb, it is this potential difference that causes the electric current to go through the light bulb. For the purpose of this chapter, it is important not only to be aware of this cause-effect-relationship between voltage and current, but also to realize that the higher the voltage, the higher the electric current through the light bulb.

4 Students' conceptual difficulties with cells and circuits

The science education literature clearly shows that DC circuits represent a great challenge for many learners (Burde, 2018; McDermott & Shaffer, 1992; Rhöneck, 1988; Waltner et al., 2009). This section therefore provides an overview of three misconceptions of cells and circuits that we think should be part of a modern teacher education curriculum. Based on our shared observation at Wits and Tübingen that these misconceptions are widespread among teaching students, we believe that this calls for the development of PCK within the framework of national school curricula (Goes et al., 2020).

However, because of the mindset and institutional structures that treat chemistry and physics as separate subjects, school curricula and the teacher preparation curricula may in fact be contributing to the misconceptions described in this section. The consequence of this silo mentality is that chemistry teachers deal with electrochemical cells and physics teachers with DC circuits, and each does so with little reference to the other. The latter are uneasy teaching about how the cell works, partly out of ignorance and partly out of conformity with curriculum specifications. At the same time, chemistry teachers often take little interest in the "external circuit", focusing instead on the significance of electrode potentials and their interpretation.

Moreover, language and terminology are important for helping students develop a good understanding of circuits. Based on our experience at Wits and Tübingen, students should be made aware of ambiguous language that can cause confusion. For example, the terms cell and battery are not interchangeable. The full name for a battery is a battery of cells, and they are in series. Similarly, the electric current represents a flow of charges. The charges (be they ions or electrons) may be said to flow, but not the current. Hence current can neither "flow" nor be stored.

4.1 Misconceptions regarding the cell

Looking at the misconceptions about DC circuits, it becomes clear that, among other factors, they can also be attributed to an unwillingness to understand how the cell works. Regular teaching does not explain circuit phenomena adequately if cells are simply described as a store of energy, a source of energy, a source of voltage, or a source of current. Such descriptions may be correct, but unless they are investigated more concretely, learners will make up the details for themselves. And, like the scientists of the early 19th century, they will often get them wrong.

Teachers of chemistry are often astonished by the ideas their students have about electrochemical cells. Some of these were reported many years ago by Garnett and Treagust (1992), and Ogude and Bradley (1994). A more recent report by Sesen and Turhan (2013) listed more than 20 misconceptions, and research into students' understanding of electrochemistry concepts continues (Karamustafaoğlu & Mamlok-Naaman, 2015). On the whole, chemistry teachers focus mostly on voltaic cells and their equilibrium properties, emphasizing electrode potentials and their application and interpretation. Most curricula identify redox reactions as the type of reaction to be found in cells, and in many senior secondary schools, the cell emf is explicitly related to the free energy change of the reaction. Electric current is more prominent in the teaching of electrolytic cells and the link is between the amount (mol) of chemical change and the quantity (C) of electricity. This link, studied by Faraday in the 1830s, was key evidence that there is a particle of electricity, which was later given the name electron. The Faraday constant, F (96 485 C / mol), indicates his name as the discoverer of the link.

One of the most widespread of all misconceptions is a product of the emphasis on the electric current in, and continuity of, the electric circuit. This leads to the following misconceptions:

- Electrons flow not only through the electric circuit, but also through the cell itself (Ogude & Bradley, 1994).
- The electrons passing through the cell are re-energized as they do so, in ways that are not satisfactorily explained.
- The current is the cause of potential differences in the circuit (Cohen et al., 1983).
- The cell stores electric current and releases it when the circuit is completed.

None of these is true. Their origin is probably in teaching and learning about circuits rather than cells. Some models used in teaching about DC circuits explicitly state or imply the first two of these misconceptions (Stocklmayer & Treagust, 1994). Other models simply ignore the inner workings of the cell. By paying more attention to the role and functioning of a cell in teaching electric circuits at an early stage, such misconceptions could be avoided or at least ameliorated.

Another area of confusion is linked with the meaning of the + and – symbols when they appear in diagrams and are described as positive and negative. The terminal signs suggest they have charges and use of the descriptors “positive” and “negative” reinforce this interpretation. These are sometimes invoked in accounting for the direction of electron flow in the external circuit, e.g., negative electrons move towards the + terminal. Unfortunately, within the cell, the + terminal is the external manifestation of the cathode inside the cell, towards which cations move. These cations may or may not accept electrons from the cathode, depending on the presence of neutral molecule competitors. In short, the idea that the + terminal has a positive charge may have a simple appeal, but it is untenable. Finally, the cell is described as a store of energy, implying that in some form or other, energy is trapped inside the cell. This view echoes the old phlogiston theory, which was overthrown primarily through the work Lavoisier carried out at around the time that Volta made his pile. The cell may be described as a source of energy, but it should be clarified that it is the redox reaction inside it that is the actual source of energy (Schmidt-Rohr, 2018).

4.2 Problems understanding the circuit as a system

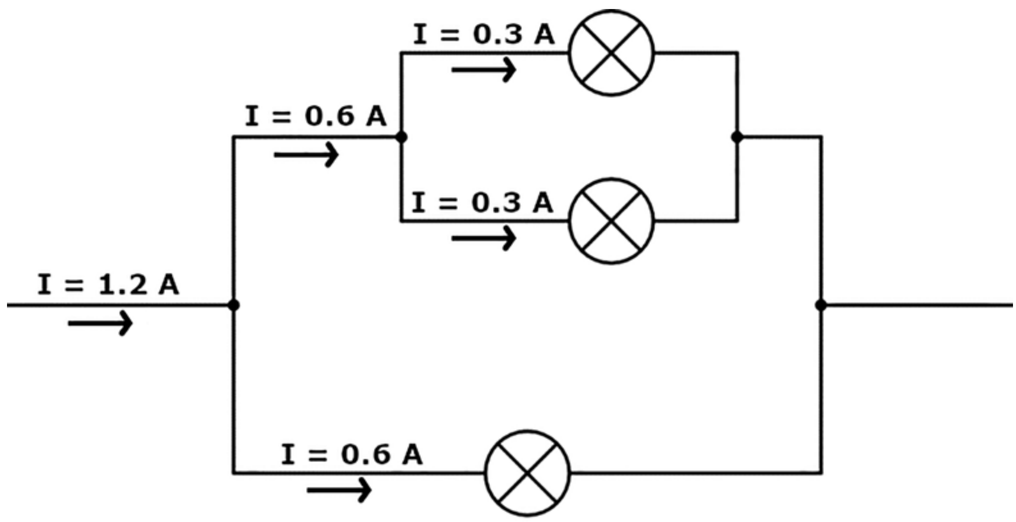

Figure 1 The circuit diagram shows the distribution of current as assumed by students with "local reasoning". All light bulbs in the circuit have the same resistance.

From a physics perspective, a major difficulty for students is understanding that the electric circuit constitutes an interconnected system. Students tend to analyze electric circuits exclusively from the perspective of the charge flow believed to travel sequentially around the circuit, component by component (Shipstone, 1984). In a parallel circuit like that shown in Fig. 1, for example, students often believe that the electric current divides into equal parts at each junction – completely ignoring the effects of the other components in the circuit and the role of potential differences. As a result of this particular misconception, often referred to as "local reasoning" (Closset, 1984), students assume that the two upper bulbs in the parallel circuit in Fig. 1 should shine less brightly than the lower bulb, when in fact all have the same brightness. This example also illustrates the problems that arise if current rather than voltage is the students' primary concept. However, if students were taught to first analyze the potential differences (p.d.) in the circuit, they would realize that the p.d. is the same across all three light bulbs. Since the same p.d. leads to the same current through identical light bulbs, all three light bulbs in Fig. 1 shine equally brightly.

4.3 Voltage as a property of the electric current

In physics education research, voltage has proven to be a quantity that presents many learners with particular difficulties, as it is often perceived as a property or component of the electric current rather than an independent physical quantity, even after instruction (Burde, 2018; Rhöneck, 1986). In particular, research has shown that students often think of voltage as the "force" or the "strength" of the electric current. This kind of reasoning about electric circuits is problematic for at least two reasons: firstly, because students fail to realize that voltage, as a potential difference, represents an independent physical quantity that refers to two points in a circuit and that can exist independently of an electric current (Maichle, 1982). As a result, students wrongly believe that, in a simple circuit attached to a battery, you can measure the voltage at a closed switch but not across an open switch (Rhöneck, 1981). Second, some students believe that the electric current simply exists in the circuit, seeing no need for a cause-and-effect-relationship between voltage and current (Cohen et al., 1983). The students' development of an independent concept of voltage is further complicated by the often extensive quantitative study of Ohm's law in the classroom. In particular, there is a danger that the traditional focus on the formula $V = R\,I$ strengthens the students' misconception that voltage is not an independent physical quantity, but a property of the electric current, since the formula seems to suggest that voltage V is always proportional to the electric current I (Muckenfuß & Walz, 1997; Rhöneck, 1988).

5. Towards an understanding of circuits as physico-chemical systems

Whilst there is much of interest to be learnt from the perspective of physics and that of chemistry, we are convinced that understanding DC circuits requires both perspectives. Drawing on our research and different curricular experiences at Wits and Tübingen, we suggest overcoming the traditional silo mentality when discussing electrochemical cells and electric circuits in science teacher education, and helping prospective science teachers understand circuits as physico-chemical systems. By integrating the two perspectives, learners in schools and in teacher education courses can develop a more holistic understanding. This suggested integration by the authors of Wits and Tübingen is highly relevant for science teacher education, as it should result in far fewer alternative conceptions arising. Such an ambition is, in principle, readily achievable in the context of a physical science curriculum, as in South Africa. Where separate physics and chemistry curricula are in force, as is the case at Tübingen University, this may be less easy, but certainly not impossible. Having reached a shared view on desirable developments and research in teaching about cells and circuits, the following sub-sections, 5.1 and 5.2, describe the current thrusts of our two groups.

5.1 Design of an interdisciplinary topic in a B. Ed. course for prospective teachers of Physical Sciences – a view from Wits

Students in this degree bring with them the knowledge about cells and circuits they acquired in school, much of it fragmentary and some of it erroneous. They would most likely be taught something about cells and circuits in the 3rd and / or 4th year of the B. Ed. curriculum. The chemistry content and the physics content are taught separately and usually in different years. These facts and the preceding analysis has led us (Bradley & Moodie, 2021) to the following design of a proposed interdisciplinary topic, probably most suited to the 3rd year of the B. Ed.

1. Sources of Energy and How They Transfer Energy
   Combustion of fuels and using cells and batteries

2. Why is Combustion of Fuels a Source of Energy?
   Differences in electronegativity of atoms results in exothermic redox / electron-transfer reactions

3. Cells as a Source of Energy
   Redox reactions in a hydrogen fuel cell and in a traditional 1.5 V cell

4. How Can Electron Transfer Take Place Through an External Circuit?
   Reductant (electron donor) separated from oxidant (electron acceptor), electron transfer externally and ion migration internally. The + and – symbols on the cell.

5. How the Source of Energy is Quantitatively Described
   Volts and kJ / mol: the link explained

We envisage that this topic would be a worthwhile basis for teaching more purely chemistry concepts (standard electrode potentials, Nernst equation) and more purely physics concepts, as exemplified in the following sub-section 5.2. It would also support teaching about alternative energy sources and energy storage. At the time of writing, it has not yet been possible to debate the teaching of this topic with our colleagues, primarily due to the additional stresses resulting from the COVID-19 pandemic.

5.2 New approaches to teaching about circuits for prospective teachers of physics – a view from Tübingen

Most students enrolled in the physics teacher course at Tübingen University do not choose chemistry as their second subject. However, as prospective physics teachers, they mostly attend the same physics lectures as their peers studying for a Bachelor of Science (B.Sc.). As a result, students in Tübingen usually have well-founded content knowledge in physics, but not in chemistry. Despite their advanced understanding of electricity, for instance, many students still hold various alternative conceptions of electric circuits. Considering their lack of content knowledge in chemistry, it is necessary to provide prospective physics teachers with an understanding of the important role that cells play in electric circuits, as well as in the electrochemical processes taking place inside these cells. Furthermore, it is essential to enhance their PCK on simple circuits by familiarizing them with typical alternative conceptions and introducing them to effective, research-based teaching approaches. Considering that educational research on cells and circuits has rarely been brought together, and taking typical alternative conceptions into account, teacher education at institutions where separate physics and chemistry curricula are in force, such as Tübingen University, may be improved if the following aspects are taken into account:

A. Discussing cells before circuits
B. Discussing open circuits before closed circuits
C. Illustrating potential differences using effective models and analogies

The following sections will elaborate the rationale for each of these three aspects based on research by the Tübingen-based author, exchanges with the authors from Wits, and findings from science education research of the past decades.

5.2.1 Discussing cells before circuits

Building on the ideas of Cohen et al. (1983), Psillos et al. (1988), Burde (2018) and their "voltage first approach", cells should not be treated as a black box at universities with separate physics and chemistry curricula, but as the starting point for a more in-depth study of circuits. It should be pointed out that the configuration of materials and substances inside the cell will enable it to produce a constant voltage as soon as its terminals are connected, but its current output will depend on the resistance in the connection. This is particularly important as many students think of cells as a source of constant current rather than constant voltage. Studying the electrochemical processes in a cell at the beginning of a unit on circuits could also counteract the development of the alternative conception that electrons do not only flow through the circuit, but also flow through the cell, getting re-energized along the way.

Another argument in favor of studying the chemical processes of cells is that it will help students better understand the role of ions and electrons in circuits. Such an approach not only facilitates an understanding of the Drude model (Drude, 1900), helping students develop deeper insight into the conduction processes (e.g., the collisions between electrons and the ion lattice), it would also make them aware of how closely chemical and physical aspects of the electric circuit are interrelated. Overcoming the traditional silo mentality between chemistry (teaching only the working of cells) and physics (teaching only the working of circuits) at the beginning of the topic "electric circuits" becomes particularly important in view of the increasing socio-economic prominence of batteries in our world, e.g., in smartphones and electric cars.

5.2.2 Discussing open circuits before closed circuits

Since the electric current often dominates students' thinking of electric circuits (Cohen et al., 1983; Maichle, 1982; Rhöneck, 1986), it is important to focus on open rather than closed circuits after studying how cells work. The reason for this is that in closed circuits, voltage and current, according to the formula $V = R\,I$, only ever occur simultaneously. This may make it more difficult for students to develop an independent concept of voltage and instead foster the alternative conception that voltage is a property of the electric current. As there is no current in open circuits, such circuits are ideal for illustrating that voltage is an independent physical quantity (Burde & Wilhelm, 2021). Furthermore, such an approach would be consistent with the ideas of Cohen et al. (1983) and Psillos et al. (1988), who, considering that the electric current often dominates teaching, called for a curriculum that starts with the concept of voltage rather than current, as “first impressions are strong and may impede a later, more rigorous, study of electricity” (Cohen et al., 1983, p. 411).

5.2.3 Illustrating potential differences using effective models and analogies

Given the importance of conceptually understanding voltage as a potential difference for an adequate understanding of electric circuits, it is important that science teachers-in-training are aware of models and analogies that have proved effective in science education research. In particular, such models and analogies should help students understand three important aspects of circuits: firstly, that voltage refers to two points in a circuit; secondly, that there is a current only when a voltage is present, and thirdly, that electric circuits represent interconnected systems, which cannot be exclusively analyzed from the perspective of charge flow.

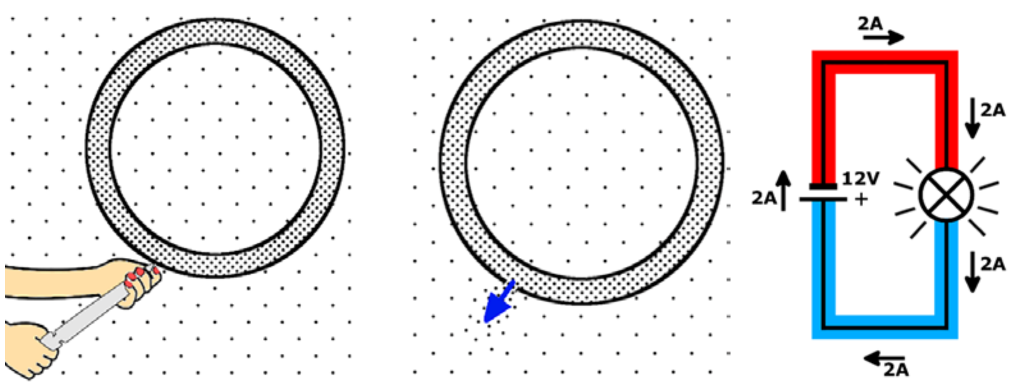

Figure 2 Just as air pressure differences cause air flow (left) from an inflated bicycle tire (blue arrow), electric pressure differences cause electron flow through a light bulb (right)

A promising way to help students develop a qualitative understanding that voltage refers to two points in a circuit and that there is a current only when a voltage is present is the use of an air pressure analogy (Steinberg & Wainwright, 1993). By comparing potential differences with air pressure differences in electric circuits, students can relate the rather abstract physical quantities “electric potential” and “electric potential difference” to their everyday experiences. In particular, students can have first-hand experience with air pressure using everyday objects such as air mattresses or bicycle tires to learn that air pressure differences are the cause of air flow (see Fig. 2). In the next step, their understanding of air pressure can be transferred to electric circuits, helping them develop a qualitative understanding of voltage by comparing the electric potential in circuits to an “electric pressure”. It can then be argued that just as air pressure differences cause air flow, electric pressure differences cause electron flow, e.g., through a light bulb. By color-coding the “electric pressure” in the wires as shown in Fig. 2, students can easily identify potential differences in various circuits.

Moreover, a key advantage of this “electric pressure” model in combination with color-coding is that it helps make voltage rather than current the students' primary concept when analyzing electric circuits. This may, for example, reduce students' tendency to reason locally and help them understand that the electric circuit represents an interconnected system (Burde & Wilhelm, 2021). Furthermore, the suggested approach helps students develop an intuitive understanding of the cause-and-effect relationship between voltage and current in circuits.

6 Visions for science teacher education in an electrical future

In this chapter we have focused on our research on students' understanding of voltage, cells and circuits as physico-chemical systems. However, these aspects point to a broader concern, namely that students should begin to see the world as an interconnected set of systems that affect each other. The global efforts to end the world's dependence on energy from fossil resources and move toward a more sustainable future following the Paris Climate Agreement (United Nations, 2015) has created a focus on renewable energy systems, such as photovoltaic cells and wind turbines. Batteries and fuel cells using hydrogen produced via these systems are now critically important technologies. From an educational perspective, it is essential that these more recent developments also find their way into school and university curricula.

The UN's (United Nations, 2021) call for “Education for Sustainable Development” demands a response from those engaged in science teacher education. Prospective science teachers should therefore not only have adequate content knowledge, but also be aware of its relevance for society and everyday life by addressing STS (“Science, Technology, and Society”) aspects of electricity (Solomon & Aikenhead, 1994). Education for Sustainable Development must be designed on such principles, which means making the walls between disciplinary silos more permeable.

3

Literature

Bradley, J. D., Khulu, S., Moodie, P., & Mphahlele, M. (2019a). Pre-service teachers' misconceptions about current and potential difference in electric circuits—using microscience kits in a POE activity. *African Journal of Chemical Education, 9*(3), 75–96.

Bradley, J. D., Khulu, S., Moodie, P., & Mphahlele, M. (2019b). Using microscience kits to address a student-teacher misconception in electric circuits: at the interface between chemistry and electricity. *African Journal of Chemical Education, 9*(3), 37–45.

Bradley, J. D., & Moodie, P. (2021). A systemic approach to teaching and learning about electrical cells and circuits using two big ideas of science. *African Journal of Chemical Education, 11*(1), 1–14.

Burde, J. P. (2018). *Konzeption und Evaluation eines Unterrichtskonzepts zu einfachen Stromkreisen auf Basis des Elektronengasmodells* [Conception and evaluation of a teaching concept for simple electric circuits based on the electron gas model], Vol. 259. Logos-Verlag.

Burde, J. P., & Wilhelm, T. (2017). Modelle in der Elektrizitätslehre [Models in electricity science]. *Unterricht Physik, 28*(157), 8–13.

Burde, J. P., & Wilhelm, T. (2021). Teaching electric circuits with a focus on potential differences. *Physical Review Physics Education Research, 6*(2).

Closset, J. L. (1984). Woher stammen bestimmte "Fehler" von Schülern und Studenten aus dem Bereich der Elektrizitätslehre? Kann man sie beheben? [From where do certain "mistakes" made by pupils and students in the field of electricity come from? Can they be fixed?]. *Der Physikunterricht, 18*(2), 21–31.

Cohen, R., Eylon, B., & Ganiel, U. (1983). Potential difference and current in simple electric circuits: A study of students' concepts. *American Journal of Physics, 51*(5), 407–412.

Duit, R. (2009). *Bibliography—STCSE: Students' and teachers' conceptions and science education.* IPN—Leibniz-Institut für die Pädagogik der Naturwissenschaften. http://archiv.ipn.uni-kiel.de/stcse/ [25.06.2021].

Garnett, P. J., & Treagust, D. F. (1992). Conceptual difficulties experienced by senior high school students of electrochemistry: Electric circuits and oxidation-reduction equations. *Journal of Research in Science Teaching, 29*(2), 121–142.

Goes, L. F., Fernandez, C., & Eilks, I. (2020). The development of pedagogical content knowledge about teaching redox reactions in German chemistry teacher education. *Education Sciences, 10*(170).

Karamustafaoğlu, S., & Mamlok-Naaman, R. (2015). Understanding electrochemistry concepts using the POE strategy. *Eurasia Journal of Maths, Science and Technology Education, 11*(5), 923–936.

KMK. (2020). *Bildungsstandards der Kultusministerkonferenz* [Educational standards of the Standing Conference of the Ministers of Education and Cultural Affairs]. Kultusministerkonferenz. https://www.kmk.org/themen/qualitaetssicherung-in-schulen/bildungsstandards.html#c5034 [25.06.2021]

Maichle, U. (1982). Schülervorstellungen zu Stromstärke und Spannung [Pupils' ideas about current and voltage]. Naturwissenschaften im Unterricht. *Physik/Chemie, 30*(11), 383–387.

McDermott, L. C., & Shaffer, P. S. (1992). Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding. *American Journal of Physics, 60*(11), 994–1013.

Muckenfuß, H., & Walz, A. (1997). *Neue Wege im Elektrikunterricht* [New ways of teaching electrics] (2nd rev. ed.). Aulis Deubner.

Ogude, N. A., & Bradley, J. D. (1994). Ionic conduction and electrical neutrality in operating electrochemical cells: Precollege and college student interpretations. *Journal of Chemical Education, 71*(1), 29–34.

Pardhan, H., & Bano, Y. (2001). Science teachers' alternate conceptions about direct-currents. *International Journal of Science Education, 23*(3), 301–318. https://doi.org/10.1080/095006901750066538

Psillos, D., Tiberghien, A., & Koumaras, P. (1988). Voltage presented as a primary concept in an introductory teaching sequence on DC circuits. *International Journal of Science Education, 10*(1), 29–43. https://doi.org/10.1080/0950069880100104

Rhöneck, C. v. (1981). Schüleräußerungen zum Begriff der elektrischen Spannung beim Erklären der Meßwerte am Schalter [Pupils' comments on the concept of electrical voltage when explaining the measured values on the switch]. Naturwissenschaften Im Unterricht. *Physik/Chemie, 29*(6), 210–215.

Rhöneck, C. v. (1986). Vorstellungen vom elektrischen Stromkreis und zu den Begriffen Strom, Spannung und Widerstand

[Ideas about the electric circuit and the concepts of current, voltage and resistance]. *Naturwissenschaften Im Unterricht—Physik, 34*(13), 10–14.

Rhöneck, C. v. (1988). Wege zum Spannungsbegriff [Ways to the concept of voltage]. Naturwissenschaften Im Unterricht. *Physik/Chemie, 36*(31), 4–11.

Schmidt-Rohr, K. (2018). How batteries store and release energy: explaining basic electrochemistry. *Journal of Chemical Education, 95*, 1801–1810.

Sesen, B. A., & Turhan, I. (2013). Inquiry-based laboratory activities in electrochemistry: High school students' achievements and attitudes. *Research in Science Education, 43*, 413–435.

Shipstone, D. M. (1984). A study of children's understanding of electricity in simple D.C. circuits. *European Journal of Science Education, 6*(2), 185–198.

Solomon, J., & Aikenhead, G. (Eds.). (1994). *STS education: International perspectives on reform*. Ways of knowing science series. Teachers College Press.

Steinberg, M. S., & Wainwright, C. L. (1993). Using models to teach electricity—the CASTLE project. *The Physics Teacher, 31*(6), 35–357.

Stocklmayer, S. M., & Treagust, D. F. (1994). A historical analysis of electric currents in textbooks: A century of influence on physics education. *Science & Education, 3*(2), 131–154. https://doi.org/10.1007/BF00486388

TüSE (2019). Der Leitfaden für Lehramtsstudierende [The guide for teaching students]. https://uni-tuebingen.de/de/197827.

United Nations. (2015). *Paris Agreement.* https://unfccc.int/sites/default/files/english_paris_agreement.pdf [25.06.2021].

United Nations. (2021). *Education for Sustainable Development.* https://en.unesco.org/themes/education-sustainable-development [25.06.2021].

Waltner, C., Späth, S., K., D., & Wiesner, H. (2009). Einführung von Stromstärke und Spannung—Ein Unterrichtskonzept und Ergebnisse einer Vergleichsstudie [Introduction of amperage and voltage—A teaching concept and results of a comparative study]. In D. Höttecke (Ed.), *Entwicklung naturwissenschaftlichen Denkens zwischen Phänomenen und Systematik: Jahrestagung der GDCP in Dresden 2009* (Vol. 30) (pp. 182–184). Lit-Verlag.