Using the Electron Gas Model in Lower Secondary Schools—A Binational Design-Based Research Project

Claudia Haagen, Jan-Philipp Burde, Martin Hopf, Verena Spatz and Thomas Wilhelm

Abstract Students' understanding of introductory electricity concepts can be fragmented even after instruction. Several reasons for this have been identified: electricity is an abstract and complex topic and traditional instruction frequently fails to meet students' learning needs. As a consequence, conceptual change is not triggered and misconceptions prevail. Research findings show that the concept of voltage, in particular, presents many difficulties for students. This paper presents a research project from four working groups whom are collaborating to develop a teaching strategy for introductory electricity at lower secondary schools which is based on the electron gas model. Additionally, research finding from one project partners' implementation of this teaching approach in a pilot study are reported. The concept of voltage is introduced as an electric pressure difference across a resistor in an electric circuit. The evaluation of this approach with more than 700 high school students shows very promising results. Based on these findings, a Design-Based Research project has been jointly developed between two German and two Austrian Universities. The aim of this study is to find out whether the significantly better performance of students instructed according to the electron gas model can be replicated with a wider sample of teachers and students across the project partners' locations.

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Introduction

Electricity is one of the major topics of the physics curriculum in secondary schools. Electricity and electronic devices are essential parts of our daily life. Nowadays, we can hardly imagine a world without electronic devices. In our daily routines, we have to make decisions which require at least a minimal knowledge about electricity: What voltage batteries do we need for the TV remote control? Which charging unit supplies the appropriate voltage for charging our mobile phone? Why is it dangerous to put a fork into the toaster to get a slice of toast out of it?

Moreover, it is of course important to know that many processes in the human body are based on electrical impulses and signals. Additionally, there are social issues related to electricity, such as, sustainable consumption or alternative energy sources etc., which requires a level of scientific literacy in this field. Thus, a basic understanding of electricity is fundamental for our daily private and professional life as well as for active citizenship.

A basic understanding of electricity includes, above all, a correct conceptual understanding of simple electric circuits and the key concepts of current, voltage and resistance. Although electricity is a main topic in lower and upper secondary schools, many students develop only a fragmented understanding of the basic physical concepts of electric circuits during secondary education. This phenomenon is not particularly new or limited to a certain age group. McDermott and van Zee [1] observed that, even university students, frequently interchanged the words current, energy, power, voltage, and even electricity when talking about circuits.

Research findings also highlight the idea that current is consumed in a circuit is still maintained by students even after instruction [2]. Another major challenge is the concept of voltage. It is particularly difficult for students to distinguish between electric current and voltage. Frequently, students only operate with the concepts of current and resistance and consider voltage as a property of electric current. In general, the concept of electric current seems to determine students' understanding of electric circuits. As a consequence, it is not necessary for them to conceptualize voltage as an independent physical quantity.

Studies on students' learning and conceptions in introductory electricity have been given considerable attention in the past three decades. Insights about domain specific learning have, however, rarely affected school teaching practice, since knowing students' alternative conceptions does not necessarily mean that educators have practical methods to promote students' conceptual change. As conceptual change is often not triggered by conventional instruction, misconceptions prevail. Subsequently, students' understanding of introductory electricity remains in many cases fragmented, even after instruction. Several reasons can be identified for this: electricity is an abstract and complex topic and traditional instruction frequently fails to meet students' learning needs. The design of successful learning environments needs to merge subject matter knowledge with student perspectives (contexts, interests, etc.) and learning needs.

Motivation

We find, at least in German speaking countries, that reviewing the content of school textbooks reveals that the introduction of electricity is mainly based on the concepts of current, resistance and voltage, while the concepts of potential and potential difference are hardly addressed [3]. From the perspective of subject matter knowledge, voltage refers to a potential difference by definition. In conventional educational reconstructions of the topic electricity, the key idea of voltage as a potential difference is, however, hardly ever included. Taking students' learning paths into account, it seems to be quite likely that a better understanding of the concept of voltage requires an understanding of the concept of electric potential first [4]. In physics education research, numerous studies have concluded that the introduction of voltage as potential difference supports students' learning needs [5–7].

Examples of such approaches include the "*flat water circuit analogy with a double water* column" as shown in Fig. 1 [8, p. 35] and the 'stick model' developed in Munich [7] as illustrated in Fig. 2. In both teaching concepts, "the visual representation of the potential has proven to be an important factor for the learning success as it facilitates the build-up of a mental model of the electric potential [7, p. 70; 8, p. 35]" [3, p. 27].

Based on these findings, which support the introduction of voltage as potential difference, Burde and Wilhelm [3] have developed a teaching approach for introductory electricity which uses a content structure based on the electron gas model. In an intervention study with a control group of students, the teaching approach based on the electron gas model was shown to lead to significantly better learning outcomes for the intervention group [10].

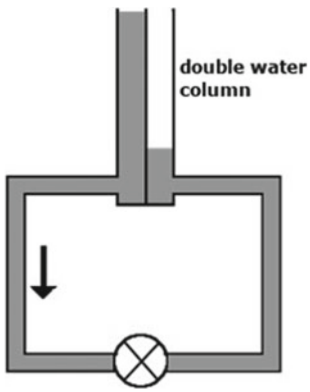


Fig. 1 The flat water circuit analogy: a double water column visualises the potential difference

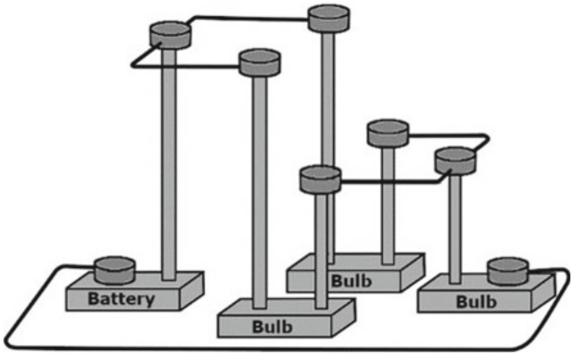


Fig. 2 The stick model [9, p. 122]: sticks positioned in different heights above the base visualize the electric potential difference

Based on these findings, a Design-Based Research (DBR) project has been jointly developed by two German and two Austrian universities. The aim of this study is to examine whether the significantly better performance of the control group of students instructed with the electron gas model can be replicated with another sample of teachers and students at the project partners' locations. In addition, it is of interest if variations concerning contexts used can stimulate students' interest.

The Electron Gas Model—Previous Findings

It is well known that students base their understanding of simple electric circuits on the concepts of current and resistance [11] and thus fail to develop a solid conceptual understanding of the concept of voltage. However, previous research studies suggest that the explicit introduction of voltage as potential difference represents a successful approach. This idea was exploited by Burde and Wilhelm [12, 13] who developed a teaching approach, which is based on the electron gas model: Building on students' prior knowledge about air pressure, voltage is introduced as an electric pressure difference across a resistor in an electric circuit. The intention of the teaching approach based on the electron gas model is to facilitate a qualitative and solid concept of electric potential so that students are able to analyze simple circuits appropriately. In terms of learning theories, this approach builds on diSessa's "Knowledge in Pieces" theory [14, 15] which stimulates conceptual development by building on students' prior knowledge. In this study, students' intuitive understanding of air pressure serves as a qualitative model of the electric potential in conducting wires.

Burde and Wilhelm specify the analogy between air pressure and voltage as follows:

> It is important to note that we are not talking about the physical pressure concept in the technical sense of a state variable here, but an intuitive prototype concept of 'pressure' in the sense that compressed air tries to push itself out of a container, e.g. based on everyday life experiences with air pumps, bicycle tires or air mattresses. [3]

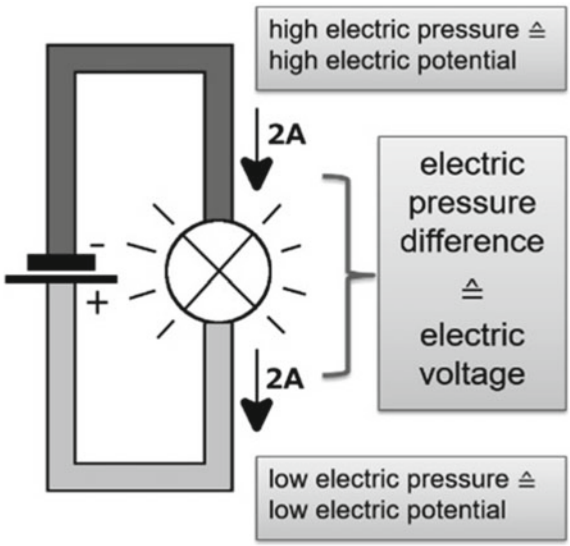
The air analogy is more compelling to learners than the water analogy, mainly because of the palpable compressibility of air and the fact that students gather experiences with the compressibility of air in everyday life (e.g. bicycle tires or air mattresses). In contrast, water is often perceived by students as an incompressible fluid and they have hardly any experience with water pressure from everyday life. Because water under high pressure differs neither visibly, nor palpably, from water under low pressure, the water analogy has proven to be not as helpful as commonly assumed. A more detailed discussion of the advantages and disadvantages of the water circuit analogy can be found in [10, 16].

It is quite intuitive for students that differences in air pressure cause an air flow. As an analogy, the electron gas model is used to introduce voltage as potential difference, which can be understood as electric pressure difference across a resistor. So, it is quite plausible that similarly to air pressure differences, which cause an air flow, electric pressure differences (electric voltage) cause an electric current as shown in Fig. 3.

The teaching materials based on the electron gas model were tested in a study with treatment and control group classes in schools nearby to Frankfurt (Germany) using a pre- and post-test design. For the participating teachers in this study, the intervention consisted of their participation in a short afternoon training session where the teaching materials were introduced and distributed.

The evaluation of this approach using the electron gas model with year 7 and year 8 students (N = 790) showed that the students of the treatment group not only significantly outperformed the conventionally instructed students, but also had a better conceptual understanding of voltage (see Fig. 4). A more detailed analysis of student's tests revealed that girls, especially within the treatment group, showed a smaller conceptual gain than boys, although their pre-knowledge was not

Fig. 3 The electron gas model [17]



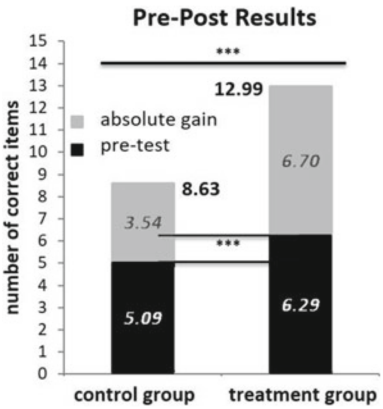


Fig. 4 Pre-post results of the control and treatment group [17]

significantly different. These results are the starting point for our bi-national DBR project, which builds on the content structure of Burde and Wilhelm [3, 10, 13] and their findings.

Goals and Research Questions

The goal of our bi-national Design-Based Research (DBR) project EPo/EKo ("Electricity with Potential/Electricity with Contexts") is to refine the content structure developed by Burde and Wilhelm [3], which proved a promotion of deeper conceptual understanding than conventional instruction. Within the framework of Design-Based Research [18, 19] the project partners aim to implement research findings in domain specific learning into school practice by offering teachers research based teaching materials and short in-service training workshops. At the same time, this project aims to gain deeper insight into students' domain specific reasoning in introductory electricity with a special focus on the concept of voltage. Another goal of the binational project is to investigate the effects of the integration of "interesting" contexts (e.g. ROSE study [20]) in the teaching concept on students' interest, self-concept and conceptual understanding. Additionally, participating teachers' pedagogical content knowledge (PCK) and its development will be investigated.

The research questions of this DBR study can be summarized as:

- Can the significantly better performance of students instructed with the electron gas model be replicated with another sample of teachers and students at project partners' locations?
- What are the effects of integrating "interesting" contexts within the teaching concept on students' interest, self-concept and conceptual understanding?

- What pedagogical content knowledge (PCK) and beliefs about teaching and learning introductory electricity do participating teachers have and how do they change due to the implementation of new teaching materials in their classes?

Research Design

The project is based on a pre-post-follow-up-design with one control and, in total, three intervention groups. Figure 5 shows the treatments for the control group and the intervention group, which consist of three different cohorts across three school years.

The group of the participating teachers (T) is the same for each year. They teach physics in a 7th grade in three subsequent years. In the first year of the project, the participating teachers (T) follow their usual approach to introductory electricity. Pre-post-follow-up-tests are administered to set a baseline for the students' performance of the cohort of year one (StY1) as can be seen in Fig. 6. A test, which focuses on the teachers' PCK facets and beliefs concerning introductory electricity is administered after the instruction. In addition, case studies are conducted with some teachers using interviews. At the end of the first year, teachers take part in a short workshop in preparation for the intervention studies which take place in the second year.

In the second year, teachers are split in two different intervention groups (T1&T2) (see Fig. 5): T1 teach their cohort of year two (StY2) focusing on context orientation and follow their usual content structure. T2 teach their cohort of year two (StY2) following the content structure of the electron gas model without focusing on context orientation. Figure 7 illustrates the research design of year two, where a pre-post-follow-up-design is used with students. This time, all student groups (StY2) function as intervention groups, revealing either the influence of the electron gas content structure or the influence of context orientation. The PCK test is again administered to teachers after they complete year two instruction. The teachers at the centre of

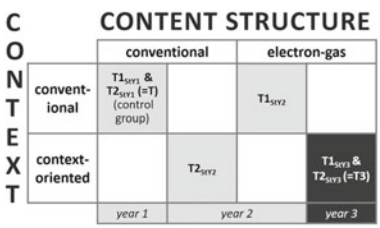


Fig. 5 Control and intervention groups in the EPo/EKo ("Electricity with Potential, Electricity with Contexts") project. T stands for the participating teachers. T1 is the group of teachers who teach the electron gas course in year 2 (EPo) and T2 is the group of teachers who teach the context-oriented course in year 2 (EKo). StY identifies the students (St) of each project year (Y). T1StY2, for example, refers to the group of students who are in the context-oriented course (T1) in the second year of the project (StY2)

the case studies are interviewed again. Finally, as in year one, the second year ends with a workshop, where the teachers are prepared for the interventions planned in the final year of the project.

In the subsequent third year, both groups of teachers (T1&T2) are combined to one group (T3), as shown in Fig. 5. The T3 teachers teach their cohort of year three (StY3) with respect to both, the content structure of the electron gas model and context orientation. The students' performance is tested again with pre-post-follow-up-tests. In parallel, the participating teachers' content specific PCK is diagnosed after the last intervention with questionnaires and interviews (see Fig. 8).

The data gained from both teachers and students will be analysed with a mixed methods approach and will be triangulated. The results gained, will then be the basis for a final development cycle of the teaching materials.

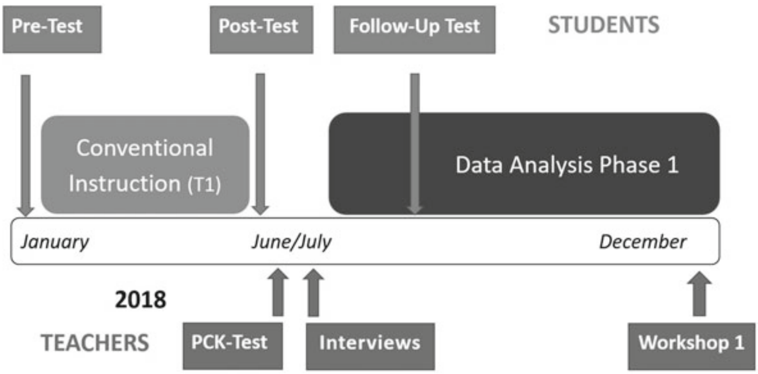


Fig. 6 Research design of year one (2018) of the EPo/EKo project

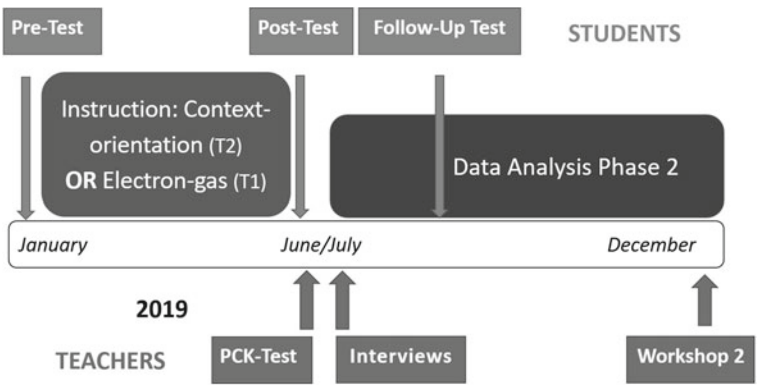


Fig. 7 Research design of year two (2019) of the EPo/EKo project

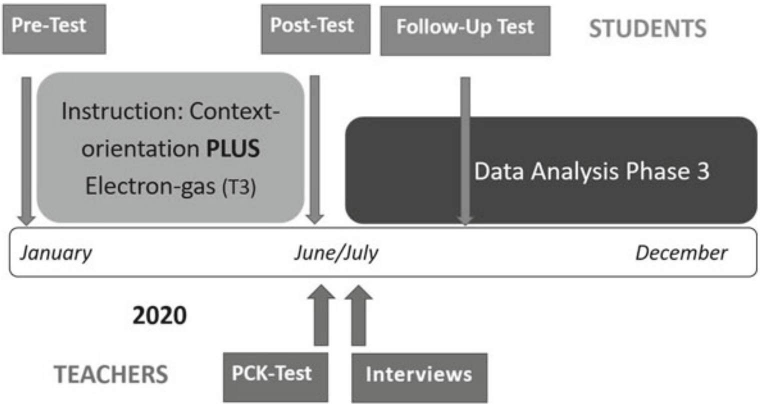


Fig. 8 Research design of year three (2020) of the EPo/EKo project

Current Status of the Project and Outlook

In preparation for the project, a concept test for students' understanding of basic key ideas of introductory electricity has been developed. Existing test instruments [11, 21] have been adapted and expanded for the purpose of our project. Currently, the first intervention phase is taking place with N = 71 classes. In parallel, we are developing a PCK test for the participating teachers. This test will be administered in spring 2018, when the teachers have finished the topic electricity in their classes.

In another strand of the project, teaching materials for the interventions of year two and three are developed in an iterative design process. First of all, materials, which operationalize conventional content structures of introductory electricity with interesting contexts are developed. These context-oriented materials are then implemented in the second year in parallel to a slightly improved version of the already existing content structure based on the electron gas model [3]. Finally, the materials for the intervention of year three are in preparation, which are characterized by the content structure of the electron gas model plus by context orientation.

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