INVESTIGATION OF STUDENT THINKING ABOUT THE VOLTAGE ACROSS OPEN SWITCHES

Master Thesis

DENISE DUDAY

TUHH
Hamburg University of Technology

ENGINEERING EDUCATION RESEARCH
FACHDIDAKTIK DER INGENIEUR-WISSENSCHAFTEN

Supervisor: Ferdinand Kieckhäfer, M. Sc.
First Examiner: Prof. Dr. Christian Kautz
Second Examiner: Prof. Dr.-Ing. Matthias Kuhl

Department for Engineering Education Research
Hamburg University of Technology

Hamburg – June 16, 2021

DECLARATION

I hereby declare that I am the sole author of this master thesis and that I have not used any sources other than those listed in the bibliography and identified as references. I further declare that I have not submitted this thesis at any other institution in order to obtain a degree.

Hamburg, June 16, 2021

Denise Duday

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

KVL Kirchhoff's Voltage Law

KCL Kirchhoff's Current Law

MC SR Multiple-Choice Single-Response

TUHH Technische Universität Hamburg

1 INTRODUCTION

The open switch is a fundamental concept in electrical engineering since it is the basis of many other electrical concepts or elements, such as the transistor. Hence, difficulties with the open switch often result in difficulties in further academic studies or electrical engineering jobs. However, a comparative study by Timmermann (2020, p.147-150) has found that over half of the students incorrectly assume the voltage across the open switch to be zero. The students were secondary school or university students.

This is a remarkable result as it indicates that the students have problems with the concept of an open switch and possibly with the general understanding of voltage. Most studies that were compared by Timmermann used the open switch as a tool to gain a deeper insight into the students' understanding of voltage. Thus, the studies used conceptual questions in the context of the open switch.

Together with the ideal current source, the open switch is the only two-terminal element for which the voltage is neither fixed nor can be determined from the current. As a consequence, the voltage across the open switch has to be determined with the Kirchhoff's Voltage Law (KVL). Students have to approach questions in the context of an open switch through the voltage. Therefore, the open switch is of particular interest for engineering education, as it provides an insight into the students' understanding of voltage.

Based on the incorrect answers about the open switch voltage, the studies that are cited by Timmermann proposed different student misconceptions. While some misconceptions are similar and hard to distinguish, others contain characteristics that separate them. Three main groups can be extracted from the proposed misconceptions.

- Voltage/current confusion
- Voltage is a substance that moves in the circuit.
- Incorrect application of Ohm's law

In this work, student misconceptions in the context of the open switch are investigated and analyzed. The proposed misconceptions from previous studies are analyzed. Semi-structured, think-aloud interviews are conducted to confirm the misconceptions that were proposed in the literature and to observe further misconceptions. The students that were interviewed are enrolled in the undergraduate course *Electrical Engineering I* at Hamburg University of Technology (TUHH). The goal of this work is to obtain a deeper insight into the students' understanding of voltage, as well as their misconceptions regarding the open switch. The following research questions of this work are used as orientations and should be answered after the interviews:

RQ1: Can the proposed misconception be confirmed?

RQ2: Can students have more than one misconception?

RQ3: How often do the different misconceptions occur?

The interviews are analyzed based on the questions above. Moreover, some students were invited for a second interview to analyze if their understanding has changed through the expanded studies in electrical engineering over the course of the lecture. The following research questions are the basis for the analysis of the second set of interviews:

RQ4: Do students have the same misconceptions as in the first interview?

RQ5: Do students have other misconceptions than in the first interview?

For the interview analysis of both sets of interviews, students' ideas are compared and similar mental models are extracted. The observed misconceptions are analyzed and described in detail with the use of student quotes.

Further, the interview analysis of both sets of interviews is used to develop a questionnaire for a quiz. The questionnaire should cover most of the misconceptions that were observed in the interviews. The goal of the quiz is to detect and/or narrow down misconceptions of students regarding the open switch as precisely as possible.

The present thesis is divided in five main parts, namely:

- Context, Methodology, Prior Research
- Interviews
- Student Misconceptions
- Questionnaire
- Conclusion

The first part contains the context, methodology, prior research. The context introduces the undergraduate course that is investigated. The methodology contains the theoretical framework and the methods that are used in this work. The prior research introduces and analyzes the studies that previously investigated student understanding of voltage in the context of the open switch. The interview part is divided into the first and the second set of interviews. Both parts cover the preparation, execution, and analysis of the interviews. The student misconceptions describe the findings in the interviews. The misconceptions are introduced, analyzed, and characterized by student quotes. The questionnaire describes the quiz development. The last part, the conclusion, contains a summary and conclusion, a reflection of the work, and a perspective on future work.

Part I

CONTEXT, METHODOLOGY, PRIOR RESEARCH

2 CONTEXT OF INVESTIGATION

In this chapter, the context of the investigation, the course *Electrical Engineering I*, is illustrated. *Electrical Engineering I* is a course at TUHH, which is taught in German.[1]

All information in this chapter regarding the course *Electrical Engineering I* are from the module manual (TUHH, 2020). The course *Electrical Engineering I* is the first course for students in the subject area of electrical engineering. It is a 6 ECTS undergraduate course with a written examination at the end of the semester.

The following subsections introduce the structure, topics, and objectives of the course. Further, the relevant topics and objectives for this work are emphasized.

2.1 STRUCTURE

The course *Electrical Engineering I* is offered in the winter semester at TUHH. The course is taught in German. The participants of the course are mostly students who just started their studies and likely have their first contact with electrical engineering in the course *Electrical Engineering I*. However, some students might retake the course or pursued a previous education in this field before this course. The participants of this course are from the studies of general engineering science, electrical engineering, data science, information engineering, and mechatronics, and add up to 400-600 students. Whereas most of these studies are directly related to the field of electrical engineering, students of general engineering might orientate their studies further away from this field. While the prior subject knowledge should not be varying a lot between the students, the motivation might do.

The lecture of this course is conducted weekly for 150 minutes. The exercises are group exercises for 90 minutes. Further, students can participate in ILIAS Test on Stud.IP to test their understanding of the topics. Every lecture's topic is concluded by an ILIAS test. Participation in the ILIAS test is voluntary.

1 As the course *Electrical Engineering I* is taught in German, the interviews were conducted in German as well. All questions that were asked in the interviews are translated into English for this work. Original material, such as e-mails and student responses are given in English and German. Further, the German conventional symbol for the voltage is U instead of V. This work uses the German convention for the voltage symbol.

2.2 TOPICS

The content of the course is divided into 8 main topics:

1. Basics of Resistive Circuits
2. Simplifying Resistive Circuits
3. Network Analysis
4. The Electrostatic Field
5. Stationary Currents in Conductive Media
6. Electrostatic Field in Non-Conductive Media
7. Static Magnetic Field
8. Induction and Time-Dependent Fields

The relevant topic of content's for this work is topic 1. Nevertheless, topics 2 and 3 might help students to gain a deeper understanding of resistive circuits and strengthen their confidence in handling resistive circuit exercises. For this reason, the interviews are conducted after topics 1-3 are taught in the lecture.

2.3 OBJECTIVES

To preserve the completeness of the course introduction in this section, the objectives of all topics are listed below:

- Kirchhoff's voltage and current laws
- Ohm's law
- Methods to simplify and analyze direct current networks
- Description of electric and magnetic fields by use of vectorial quantities
- Basic material relations
- Gauss's law
- Ampère's law
- Induction law
- Maxwell's equation in the integral form
- Concept and definition or resistance, capacitance and inductance

Students who mastered the first three objectives should be able to participate in the interviews without any struggles. However, difficulties in the interviews suggest that those objectives are not understood on a deeper level.

3 METHODOLOGY

This chapter introduces the theoretical framework of this work, as well as the used methods.

3.1 THEORETICAL FRAMEWORK

This section gives an overview of relevant theories for this work. The conceptual change theory by Posner et al., and the definition of misconception by Hammer are described.

3.1.1 *Conceptual Change Theory*

Conceptual change theories describe how existing knowledge can be the reason why new knowledge might not be enhanced. In this work, the conceptual change theory by Posner et al. is introduced. Especially important for this work is how the theory describes the occurrence of misconceptions.

Posner et al. (1982) describe the student's current understanding as their conceptual ecology. Further, they describe that observations of new phenomena can either align or contradict with the current concept ecology. If the new observations align, assimilation happens. In this process, the student can use existing knowledge and concepts to understand the phenomena. Further, the new observation is integrated into the concept ecology.

If the new observation contradicts the existing concept ecology, the students experience an anomaly. Posner et al. say one of five things can happen in case of an anomaly.

First, the student can experience accommodation. In the process of accommodation, the concept ecology would be changed for the new observation to align. Hence, accommodation is not a quick or easy process for the student. Different requirements have to be met for it to happen. First off, the student has to recognize the anomaly and consider it dissatisfying. This step is indispensable for the student to accept the fact that their concept ecology has to change. Second, the student needs to find the new observation plausible, intelligible, and fruitful to be motivated to change their concept ecology.

Apart from accommodation, one of the following four things can happen in case of an anomaly as well:

- The student could reject the new observation.
- The student could consider the new observation as irrelevant.

- The student could force the new observation to assimilate without changing their concept ecology, hence, without accommodation.
- The student could only apply the new observation in specific situations and therefore not change their concept ecology permanently.

For all those options, the concept ecology would not be changed. Instead, a misconception would arise.

Strike and Posner (1992) raise three points of critique towards the conceptual change theory by Posner et al. (1982). First, student's misconceptions do not always exist in an articulated way. Second, misconceptions are part of the concept ecology as well, and all the parts of the concept ecology need to be seen in constant dynamic. Last, the conceptual change theory was too rational.

3.1.2 *Misconceptions*

In the previous section, the term *misconception* was used to describe the enrichment of incorrect knowledge. In this subsection, the meaning of the term *misconception* is further investigated.

According to Hammer (1996) misconceptions

- are strongly held, stable structures;
- differ from experts conceptions;
- affect in a fundamental sense how students understand natural phenomena and scientific explanations;
- must be overcome, avoided, or eliminated for students to achieve expert understanding.

Goris (2012, p.39-44) describes that author uses other terms beside the term *misconceptions*, such as *alternative beliefs*, *preconceptions* and *intuitive knowledge*. Those other terms deemphasize a misconception to be a mistake. Instead, the terms are more neutral or even positive.

However, the intuitive character of the term *misconception* is the reason why it is used in this work. When using the term *misconception* is is with regard to the definition of Hammer.

3.2 METHODS

To investigate student thinking about the voltage across an open switch, different methods are used in this work. This section introduced these different methods.

3.2.1 *Conceptual Questions*

Conceptual questions test the students' understanding of concepts instead of their ability to apply memorized algorithms or equations. Mostly, an understanding of different quantities is necessary to answer conceptual questions correctly. Further, the tested concept should not be obvious to the student, as they might use memorized definitions or equations to answer the question if they detect the underlying concept.

Mazur (1997)[p.6] describes that students tend to do better on textbook questions than conceptual questions that cover the same topics. He explains that the students apply memorized algorithms to textbook questions without understanding the underlying physics. This results in false-positive answers, in which the student answers the question correctly without understanding the physics of the applied algorithms.

In this work, conceptual questions are used to determine if the students correctly understood the taught concepts. Different tasks ensure that the students cannot blindly apply memorized algorithms or equations. Further, a combination of quantities is necessary to answer the different conceptual questions correctly.

3.2.2 *Qualitative Research Methods*

Qualitative research methods are a way to obtain data in engineering courses. Other methods are quantitative and mixed research methods. The qualitative research methods are used to identify *what* students think about a concept and *why* they think so. They are used to gain an insight into the student's understanding.

As described by Borrego et al. (2009), the qualitative research methods are based on collecting and analyzing textual data, such as surveys, interviews, student explanations, and observations. The qualitative research methods that are used in this work are explained in detail in the following subsections.

3.2.2.1 *Semistructured Interview*

Wildemuth et al. (2017)[p.248-252] describes an interview as a "purposeful conversation" with the goal of data collection in the context of research studies. The authors further describe that semi-structured interviews lay between the two extremes of structured and unstructured interviews.

While structured interviews have a fixed question order and standardized wording, semi-structured interviews offer the freedom to adjust the order and the wording of the interview question, depending on the student's answers.

Unstructured interviews, on the other hand, have a general focus. The follow-up questions must be generated situation-given, based on the student's answers. In comparison to unstructured interviews, semi-structured interviews provide the advantage of preparation. If the interviewer knows possible situations in which the interview can evolve, possible follow-up questions can be prepared beforehand.

Semi-structured interviews have a broad structure but offer enough freedom in the interview to adapt questions individually to the student's answers. The goal of the interviews is to understand the student's mental model and their reasoning. Therefore, the interviews can be adapted to the students' individual answers.

DEVELOPING THE INTERVIEW GUIDE Based on the objective of the study, the interview guide is developed.

Different tasks and initial questions are devolved. Those initial questions are the same for each student. Further, follow-up questions are prepared. While the initial questions are the same for all students, the follow-up questions can vary for each student, depending on the student's response. The follow-up questions are prepared based on the knowledge of prior research. Hence, possible outcomes to the initial questions are covered.

Several tasks which vary from another but ask about the same concept, nonetheless, can be used. This is done to see if the student's answers are bound to specific conditions which are met in one task but not in the others. The different tasks are used to find contradictions or inconsistencies in the student's answers. Moreover, the variation of the different tasks should prevent the students from applying memorized algorithms.

CONDUCTING THE INTERVIEW Before the interview, general aspects such as the interview time and the interview location need to be considered.

Due to the restrictions caused by the COVID-19 pandemic, an interview environment with personal contact was not possible. For this reason, an online Zoom room was used for the interviews. The Zoom room holds the advantage of using verbal explanations as well as a whiteboard for explanations that require drawings. Further, the interviews can be recorded.

The semi-structured interviews in this work are conducted as tandem interviews, as described by Kincaid and Bright (1957). It means that two interviewers are interviewing one student.

Having more than one student per interview makes little sense, as the goal of the interview is to get a detailed insight into the student's individual understanding.

As Kincaid and Bright describe, conducting the interviews with two interviewers holds several advantages, such as efficiency, having individual differences of the interviewers, and in the interview analysis.

The interviewers can alternate in asking questions. This is especially helpful if one interviewer comes up with a follow-up that was not in the interview guide but helps to further understand the student's mental model. Further, the student always has the complete attention of one of the interviewer.

The individual differences of the interviewers can lay in different training, background, experiences, or personal qualities. Those differences can complement the interview. Further, the interviewers can support and correct each other. For example, a more experienced interviewer might balance the inexperience of the other interviewer.

Another advantage in tandem interviews lays in post-processing. The interviewers might interpret the student's statements differently. Hence, a short debriefing after the interview increases the chances of an accurate analysis. Moreover, a reflected advice of the more experienced interviewer after the interview might help in improving the following interviews.

INTERVIEW ANALYSIS The interview analysis is based on the interview videos.

As described by Borrego et al. (2009), an analysis of qualitative data is not generalizable. However, in the first step, descriptions can be extracted from the interviews. Based on these descriptions, student's answers with similar descriptions can be categorized. These categories provide information about the students' mental models, which can be analyzed in another step. In the last step, those mental models need to be compared to prior research results.

3.2.2.2 *Think-Aloud Interviews*

Wildemuth et al. (2017) describes think-aloud interviews as a method to gain information about the student's cognitive process. The student is asked to vocalize their thought process while performing a task. Therefore, the interviewer can obtain information about what happens in the student's mind.

Similarly, Jørgensen (2007) describes the goal of think-aloud interviews, to obtain the spontaneously verbalized ideas, thoughts, beliefs, etc., of the student during the task or the interview.

The purpose of think-aloud interviews is to answer the question *how* the students think about a concept and to gain a deeper insight into the student's way of thinking and their mental models.

To increase the output of the conceptual questions, the student is asked to vocalize their thoughts during the entire interview. Asking the student to think aloud increases the output of the interview as the student expresses more of their thoughts in comparison to a normal interview, and the student is less likely to filter their thoughts.

Therefore, the analysis of the student's mental model will be more accurate. Further, depending on how detailed the student explains their thought process during the interview, more or fewer follow-up questions are needed.

3.2.2.3 *Written Students' Explanations*

Another qualitative research method is written students' explanations which are written answers in tests, quizzes, or exams. The student is asked to explain a result or phenomenon. The questions are often *what* or *why* questions, which require the students to explain their mental model. Conceptual questions further reduce the possibility that the student writes down memorized textbook answers.

The student answers to the *what* or *why* questions are analyzed qualitatively, as the questions are used to detect students' mental models. Similar to the analysis of the semi-structured interviews, the students' responses are categorized into similar answers. Further, similar mental models are extracted from answers with similar ideas and compared to previous research results.

Further, written students' explanations can be used to check if the previous answers in the test match with the student's beliefs, thus, if the explanation fits the previous answer.

In this work, written students' explanation questions are suggested in the questionnaire. They are marked as "Other?" or "Explain". Both answer options should lead to text fields in which the student is asked to explain their thoughts.

3.2.3 *Quantitative Research Methods*

The quantitative research methods answer the question *if* the student answers the question correctly and understands the concept correctly. Borrego et al. (2009) describes the purpose of quantitative research methods as a way to objectively project the previous findings onto a larger number of students.

There are different kinds of questions that can be classified as quantitative questions. The types of quantitative research methods that are relevant for this work are introduced in this section.

3.2.3.1 *Multiple Choice Questions*

Multiple-choice questions can be handed to a large number of students, and their answers can be analyzed quite easily. Thus, multiple-choice questions make statistical analysis based on a larger number of students' answers manageable.

In this work, a questionnaire is developed. Multiple-Choice Single-Response (MC SR) questions are used for the questionnaire. For the case that the questionnaire is used as a student quiz, the student has to select one of several answer options. The answer options consist of the correct answer, as well as one up to three incorrect answer options. Depending on the number of answer options, the possibility of guessing the correct answer varies. The more incorrect answer options exist, the lower is the chance that the student guesses the correct answer.

In this work, the number of answer options depends on findings from the interviews. The number of answer options varies for different questions. This means that the probability of guessing the correct answer has a different probability for the question. As a consequence of having different numbers of answer options in MC SR questions, the quiz should not be used for diagnostic analysis.

3.2.3.2 *Two-Tier Questions*

The first tier is usually a question that answers the question *if* the student understood the concept, while the second tier answers the question *why* the student chose the first answer.

Timmermann and Kautz describe the design of two-tier questions. They describe that the first tier requires a fact-based response, while the second tier asks the students about an explanation. The authors describe this indirect question about the student's reasoning in the second tier as an advantage of two-tier questions.

3.2.3.3 *Multi-Tier Questions*

Findings in the interviews have shown that some students' mental models are more detailed than others. As the number of answer options of each MC SR question should be limited to a maximum of five answer options in the questionnaire, multi-tier questions are used.

A multi-tier question consists of the first tier asking *if* the student understood the concept correctly, while the following tiers answer the question *why* the student chose the first answer. The advantage of multi-tier questions is to gain a deeper understanding of the student's understanding within a written text. However, while the questionnaire was developed in this work, no quiz was given to students yet.

Further, not every mental model that was obtained in the interviews is as detailed as the other. Therefore, the different misconceptions questions within the quiz have a different number of tiers; this, as well as the inconsistent number of answer options in the MC SR questions, causes the quiz to be unsuitable for a diagnostic analysis.

3.2.4 *Combined Qualitative and Quantitative Research Methods*

Ideally, qualitative and quantitative research methods are combined to mix the advantages of both methods.

In this work, a quiz is suggested. The questionnaire to the quiz contains MC SR questions, as well as text fields that ask the student to explain the results or their thoughts. This combination of a MC SR question and a written student explanation task could be analyzed with the combination of qualitative and quantitative research methods.

The MC SR question can be analyzed qualitatively to answer *if* the student understood the concept correctly. The written student explanation can be analyzed qualitatively to answer *what* the student thinks about the concept.

The combination of qualitative and quantitative research methods can increase the output of the student's answers, while the student only has to take one test.

4 PRIOR RESEARCH

In previous studies, open switches were used as a conceptual question to gain information about the student's understanding of KVL. The method of conceptual question is explained in Section 3.2.1.

Prior studies show that students often assume the voltage across an open circuit to be zero. In a comparative study, Timmermann (2020, 148,149) evaluated the following studies:

- Engelhardt (1997),
- Smaill et al. (2012),
- Hussain et al. (2012),
- Cohen et al. (1983),
- Periago and Bohigas (2005a) and
- Timmermann (2020)

He concluded that in total 52% of the 5607 student of all studies incorrectly assumed the voltage across the open switch to be zero.

This section gives an introduction to previous studies in which open circuits were used. Section 4.1 introduced the questions that were used in prior researches, and Section 4.2 gives an overview about proposed misconceptions that were observed based on open circuit exercises.

4.1 QUESTIONS USED IN PREVIOUS STUDIES ABOUT OPEN CIRCUITS

In the literature different types of questions that ask about the open circuit voltage are used. Timmermann (2020, p.135-140) identified the following four categories:

- Open Switch Questions
- Two-Tier Questions
- Removed Bulb Questions
- Ranking Questions

The four categories of question types are used in this work as well. In this section, the different question types are shortly introduced, and corresponding literature is referenced.

4.1.1 *Open Switch Questions*

In studies about students' conceptions about the electric circuit, von Rhöneck (1982) asks about the open switch voltage. The circuit consists of an open switch in series with a bulb and a voltage source. The students are asked in an interview about the voltage across the open switch. In the DIRECT by Engelhardt (1997, p.93) a question asks about the open switch voltage. The circuit contains an open switch in series with two bulbs and a voltage source. The MC SR question asks about the open switch voltage.

Both circuits contain an open switch in series with a voltage source and bulb(s). Further, both tasks ask the students directly about the open switch voltage.

4.1.2 *Two-Tier Question*

Two-tier question were used by Sabah (2007) and Hussain et al. (2012). Both of their questions can be understood as an advancement of the DIRECT question by Engelhardt.

Sabah uses the same circuit as Engelhardt. The first tier asks about the voltage across the open switch. The second tier asks about a reason. Each answer option of the second tier fits one answer option of the first tier.

Hussain et al. use resistors instead of bulbs in their circuit. Further, the answer option in the second tier that fits the correct answer in the first tier is "Others (Please Specify)".

The first tier is similar to the DIRECT by Engelhardt for both questions by Sabah and Hussain et al.. However, in contrast to the DIRECT, the second tiers ask about a reason. As a result, the two-tier questions provide a deeper insight into the students' understanding.

4.1.3 *Removed Bulb Questions*

Cohen et al. (1983), Periago and Bohigas (2005b) and Timmermann (2020, p.139) used questions in which a bulb was removed from its socket to investigate the students' understanding of open switches. Removing a bulb from its socket opens the circuit at that point. Hence, an open circuit voltage drops across the removed bulb. All three authors use different circuit designs. However, the core idea is the same for all of them.

Questions that ask about a voltage across a removed bulb have a higher difficulty than questions that ask about an open switch voltage, as the students have to detect the removed bulb as an open circuit.

4.1.4 *Ranking Questions*

Timmermann (2020, p.140) also uses a ranking question in his investigations about the student understanding of open circuit voltages. The circuit consists of a voltage source in parallel to a bulb, which is parallel to an open switch, a bulb, and another voltage source in series. Further, the circuits consist of different measurement points A-D. The same circuit was also developed by Smith and van Kampen (2011). Timmermann asks the students to rank the voltages between every two points. The advantage of this question type is that it does not directly ask the students about the open switch voltage. Moreover, the students are asked about a reason for their choices. This question provides a deeper insight into the students' understanding.

4.2 PROPOSED MISCONCEPTIONS FROM PREVIOUS STUDIES ABOUT OPEN CIRCUITS

This section gives an overview of proposed observations and misconceptions from previous studies regarding the open switch.

Table 1 shows the authors and their observations or proposed misconceptions about the voltage across the open switch. The table lists only misconceptions and observations that are directly related to open circuit tasks.

As listed in Table 1, several authors observed similar misconceptions, although some misconceptions are formulated slightly differently. In Table 2, the misconceptions and observations from previous studies are restructured. The table summarizes misconceptions that were described by several authors and lists the authors who suggested the misconceptions. In comparison to Table 1, which was sorted based on the authors, Table 2 is sorted based on the misconceptions.

As listed in Table 2, the observations and misconceptions from previous studies regarding the open switch can be summarized into three main misconceptions, namely:

1. Current/voltage confusion
2. Voltage is a substance that moves through the circuit.
3. Incorrect application of Ohm's law

The misconceptions and observations are shortly introduced in the following subsections. Further, differences in the findings of the authors are pointed out.

Author	Observation or proposed misconception
von Rhöneck (1982)	- The electrical voltage is the strength of the electrical current - The electrical voltage is the force of the electrical current - The electric current is the cause of the electric voltage - The electric voltage flows - The electric voltage and the electric current always occur together
Engelhardt (1997)	- Current/Voltage confusion • The potential difference is a property of the current • Current and voltage always come together • Current causes voltage
Smaill et al. (2012)	- Incorrect application of Ohm's law
Hussain et al. (2012)	- Incorrect application of Ohm's law
Goris (2012)	- Current/voltage confusion • The potential difference is a property of the current • Current and voltage always come together • Current causes voltage - Voltage is a substance that circulates in the circuit
Skromme and Robinson (2015)	- Incorrect application of Ohm's law
Timmermann (2020)	- Voltage is a property of current - Voltage is caused by current - Voltage and current always appear together - Voltage is a substance that moves through the circuit - Ohm's law applies to open circuits

Table 1: Observations and proposed misconceptions in previous studies, sorted based on the authors that described the misconceptions.

Misconception	Authors that described the misconception
Current/Voltage confusion • the potential difference is a property of the current • Current and voltage always come together • Current causes voltage	- von Rhöneck (1982) - Engelhardt (1997, p.93) - Goris (2012, p.164) - Timmermann (2020, p.150-152)
Voltage is a substance that moves in the circuit	- von Rhöneck (1982) - Goris (2012, p.163,164) - Timmermann (2020, p.52)
Incorrect application of Ohm's law	- Smaill et al. (2012) - Hussain et al. (2012) - Skromme and Robinson (2015) - Timmermann (2020, p.153)

Table 2: Observations and proposed misconceptions in previous studies with authors, sorted based on the misconceptions.

4.2.1 *Current/Voltage Confusion*

The current/voltage confusion was first proposed by Engelhardt (1997, p.93). She states that students' assumptions about voltage/current confusion can be analyzed as one of the following three categories:

- Voltage and current always appear together
- Voltage is a property of current
- Voltage is caused by current

Similar, Goris (2012, p.164) used the same categorization in her work. On the other hand, von Rhöneck (1982) described the subcategories as independent observations. Similar, Timmermann (2020, p.150-152) described the three subcategories as independent misconceptions. All of these specifications of the current/voltage confusion describe a dependency of voltage on current. The three subcategories are shortly introduced, and differences in the findings of the authors are noted.

The author von Rhöneck observed that students describe the voltage as a strength or force of the current. The voltage is used to further characterize the current. Hence, voltage is described as a property of current. Further, Timmermann observed that the voltage was described as the speed of the current. As a result of this misconception, students argue that the voltage, the property of current, cannot exits without the current. Hence, no voltage would drop across the open switch in the students' mental models.

Further, students might think that current and voltage always appear together. For the case of the open circuit, where the current is zero, the voltage consequently has to be zero as well. Timmermann proposed in his work that it might be hard to distinguish this specification of the current/voltage confusion from the specification of understanding voltage as a property of current.

Moreover, students might believe that current is causing voltage. Thus, that voltage is produced by current. As a result, the voltage cannot exists if there is no current that could produce the voltage. Hence, no voltage would drop across the open switch in the students' mental models.

4.2.2 *Voltage Is a Substance That Moves in the Circuit*

The authors von Rhöneck (1982), Goris (2012, p.164) and Timmermann (2020, p.152) describe observations in which students describe the voltage as a substance that moves through the circuit. Students who have this misconception understand voltage as a substance that moves in the circuits. Observations from Goris and Timmermann indicate that the students assume that the voltage moves out of the circuit at the open switch. Another possible explanation might be that the students assume that voltage cannot start moving as long as the switch is open.

4.2.3 *Incorrect Application of Ohm's Law*

Smaill et al. (2012), Hussain et al. (2012), Skromme and Robinson (2015) and Timmermann (2020, p.153) describe that students incorrectly applied Ohm's law at the open switch and conclude that the voltage across the open switch is zero. On the one hand, Hussain et al. describes a prioritization of current in the students' mental model. Students who prioritize the current in Ohm's law first consider the values of the current and the resistance. However, when applying Ohm's law, they prioritize the current and neglect the value of the resistance. On the other hand, Smaill et al. and Skromme and Robinson describe a blind reliance on Ohm's law. Students rely on the current and do not consider the resistance of the open switch at all.

Part II

INTERVIEWS

5 FIRST SET OF INTERVIEWS

The first set of interviews was conducted to answer the following research questions:

RQ1: Can the proposed misconception be confirmed?

RQ2: Can students have more than one misconception?

RQ3: How often do the different misconceptions occur?

This chapter explains the preparation, execution, and analysis of the first set of interviews.

5.1 PREPARATION OF THE FIRST INTERVIEW SET

This preparation of the first set of interviews is explained in this section. The interview structure and the students that participated in the interviews are investigated in separate subsections.

The interviews were semi-structured, think-aloud interviews, as described in Section 3.2.2.1 and Section 3.2.2.2. The interviews have several main questions with fixed formulation and follow-up questions that are used depending on the situation in which the interview develops.

5.1.1 *Main Questions*

The main questions in the interviews are based on different circuits. The formulation of the main questions is fixed to ensure the same conditions for the students and the analysis. In the following, the different circuits and their advantages and differences are explained.

The first interview circuit of the first set of interviews is illustrated in Figure 1. It contains a series connection of a voltage source, two bulbs, and an open switch. The voltage across the open switch is the same as the voltage of the voltage source. Moreover, three measurement points are depicted in the circuit.

The points are used to ask the students about the voltage between those points, such as the voltage across the open switch, the voltage across a bulb, or the voltage across a bulb and the open switch in series. Therefore, it can be tested if the students' understanding of voltage is related to resistive elements. At the same time, it can be tested if the students assume that voltage only exists at one point. For this reason, the question that asks about the open switch voltage is formulated without mentioning the measurement points. However, depending on which points the students use for their explanations, a prediction about their understanding is possible. Moreover, the circuit's simplicity offers the advantage that incorrect answers based on misconceptions that are not related to the open switch are reduced.

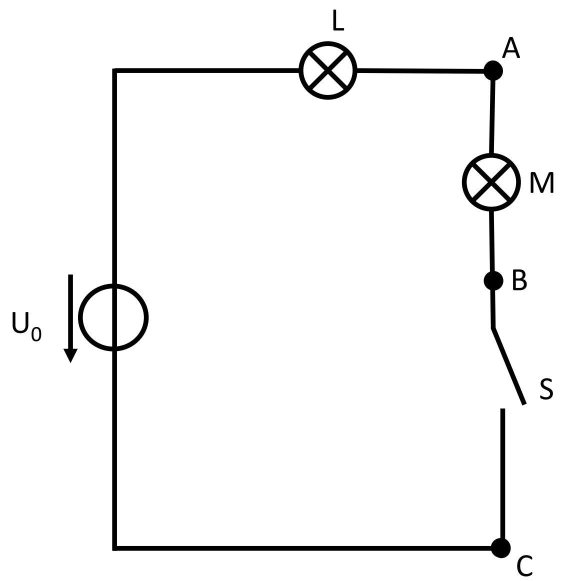


Figure 1: First interview circuit of the first set of interviews.

The second interview circuit of the first set of interviews is illustrated in Figure 2. It consists of three parallel branches. The first branch contains a voltage source in series to bulb L, the second branch contains an open switch, and the third branch contains bulb N. Further, four measurement points are depicted in the circuit. The voltage across the open switch is the source voltage subtracted by the voltage across the bulb L.

In comparison to the first interview circuit, a current is flowing in this circuit. Therefore, misconceptions that are connected to the current can be observed with the second interview circuit. Further, the second interview circuit is quite simple, as well. Thus, misconceptions that are not related to the open switch are reduced.

The third interview circuit of the first set of interviews is illustrated in Figure 3. It is more complex than the first two circuits, as it combines both. In comparison to the second circuit, the third circuit has a bulb M in series to the open switch. The voltage across the open switch is the source voltage subtracted by the voltage across the bulb L.

The higher complexity offers the advantage of testing students who correctly answered the first two circuits. Moreover, the higher complexity might reveal further misconceptions in the student's mental model as well.

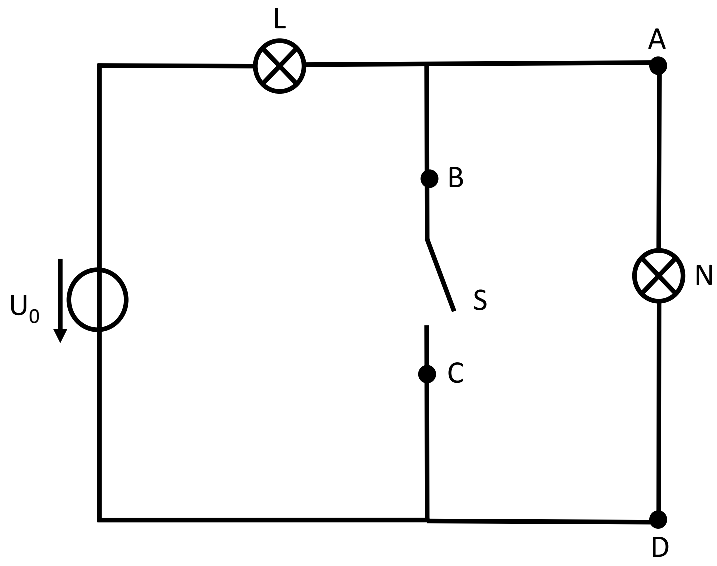


Figure 2: Second interview circuit of the first set of interviews.

Figure 4 illustrates a first variation of the second interview circuit of the first set of interviews. The branch of bulb N does not exist in this circuit in comparison to the second interview circuit, as illustrated in Figure 2. Therefore, this first variation of the second interview circuit contains a voltage source in series to a bulb and an open switch. The voltage across the open switch is the same as the voltage source.

The circuit can be used to test the assumption that the students have a misconception that is related to the current. In the second interview circuit, a current is flowing. However, in this first variation of the second interview circuit, no current is flowing. In neither of the circuits is the voltage across the open switch zero. If the first variation of the second interview circuit causes the student to state that the voltage across the open switch is zero, a current-related misconception is highly likely.

Figure 5 illustrates a second variation of the second interview circuit of the first set of interviews. In comparison to the first variation of the second interview circuit, the open switch is substituted by open terminals. The voltage across the open terminals is the same as the voltage source.

The second variation of the second interview circuit can be used to test if the student's incorrect understanding is related to the element switch or if it is a general misconception regarding open circuits.

For each circuit, several main questions were prepared. The questions have the same formulation for each student to reduce difficulties in the analysis. Each circuit asks about the open switch voltage, the bulb voltages, and whether the bulbs are lit up. Table 3 lists the main questions for each circuit.

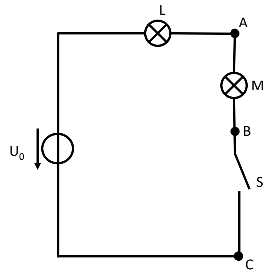
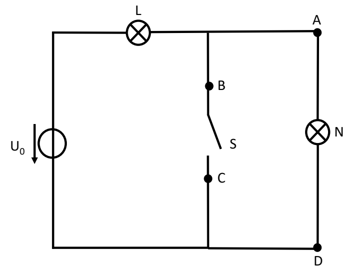
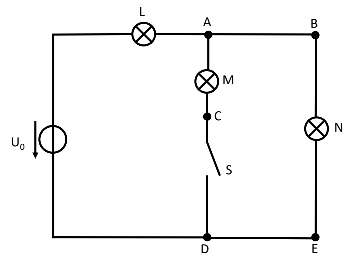
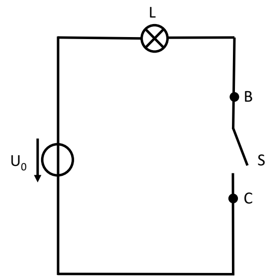
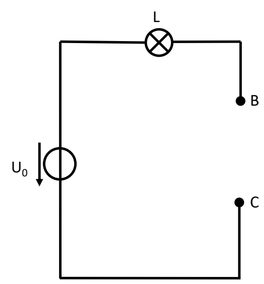
Circuit of the first set of interviews	Main questions
 Interview Circuit 1	- Maybe this first question is a little bit odd, but could you please name all the elements in the circuit? - Which bulbs are lit? Why? - What is the voltage U_{BC}? Why? - What is the voltage U_{AB}? Why? - What is the voltage U_{AC}? Why?
 Interview Circuit 2	- What is the voltage U_{BC}? Why? - What is the voltage U_{AD}? Why? - Which bulbs are lit? Why?
 Interview Circuit 3	- What is the voltage U_{CD}? Why? - What is the voltage U_{AC}? Why? - What is the voltage U_{AD}? Why? - What is the voltage U_{BE}? Why? - Which bulbs are lit? Why?
 First Variation of Interview Circuit 2	- What is the voltage U_{BC} again? Why? - Is bulb L lit? Why?
 Second Variation of Interview Circuit 2	- What is the voltage U_{BC} again? Why? - Is bulb L lit? Why? - Would you agree that this circuit looks like the equivalent circuit of an ideal voltage source? - Would you agree that no voltage drops at an ideal voltage source?

Table 3: Main interview questions for all circuits of the first set of interviews.

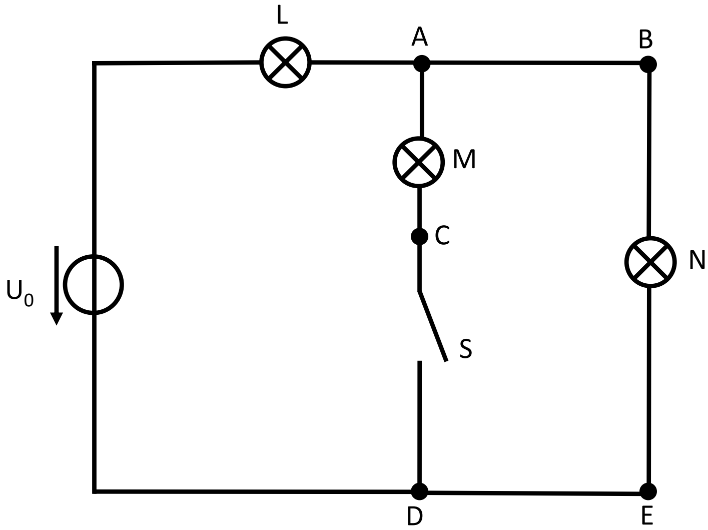


Figure 3: Third interview circuit of the first set of interviews.

5.1.2 *Follow-Up Questions*

As described in Section 3.2.2.1, semi-structured interviews offer the advantage that follow-up questions are prepared beforehand. Those follow-up questions can be prepared based on possible situations that might occur in the interviews. Since previous studies have observed different misconceptions based on open switch questions, possible interview situations are known.

Based on the observed misconceptions from previous studies, which are analyzed in Section 4.2, interview follow-up questions were developed. The follow-up questions are sorted based on the misconceptions from previous studies and are listed in Table 4.

Not all follow-up questions are used for each student. Based on the student's answers and the interview development, new follow-up questions can be asked as well.

Moreover, the follow-up questions are constantly updated by questions that were asked in an interview, but were not prepared beforehand and helped to understand the student's ideas better. Further, the follow-up questions are updated by questions that were not asked during the interview but appeared to have been useful based on the analysis of the interview.

5.1.3 *Student Recruitment*

All students that are enrolled in the course *Electrical Engineering I* at the TUHH were contacted by e-mail in the middle of November 2020. The e-mail introduced the author of this work, as well as the topic of the thesis. Further, it asked the students to participate in the interviews. It contained the expected time of the interviews, as well as the

Misconception	Interview follow-up questions
Current/Voltage confusion • the potential difference is a property of the current • Current and voltage always come together • Current causes voltage	- If voltage is the force/velocity, why is it zero across the open switch? - Asking about the voltage at different points of the circuit. - Where in the circuit is current? Where in the circuit is voltage? - Asking about relations between a current and a voltage: Does this current causes this voltage? What about the open switch voltage? - What is the voltage across the closed switch? - Can you apply KVL to this circuit?
Voltage is a substance that moves in the circuit	- Asking the student to draw the voltage into the circuit. - Asking the student to draw the current into the circuit. - Asking about the voltage at different points of the circuit. - Does the voltage flows out of the ciruit at the open switch? - Can you apply KVL to this circuit? - Where does the voltage disappear to? - Is KVL valid?
Incorrect application of Ohm's law	- Asking the student to write down Ohm's law. - What are your assumptions for the current? - What are your assumptions for the resistance of the open switch?

Table 4: Interview follow-up questions based on misconceptions that were observed in previous studies.

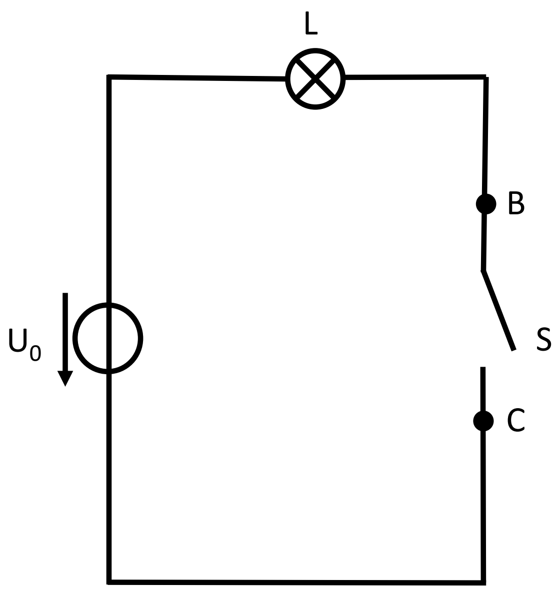


Figure 4: First variation of the second interview circuit of the first set of interviews.

interview environment. Moreover, students' advantages of participating in the interview were listed. Through the interviews, the students will be able to test their knowledge about electrical engineering. The students will get feedback about their understanding and will be able to ask questions after the interview.

Further, the e-mail contained a link for the students to book an interview appointment. The link was directly inserted into the e-mail to reduce the student's effort and inconveniences to sign up for the interview.

To the e-mail, an info sheet was attached. The info sheet answered possible questions about the interview.

Both the e-mail and the info sheet were written in German. The e-mail and the info sheet, as well as the translations, can be found in Appendix A.

5.2 EXECUTION OF THE FIRST SET OF INTERVIEWS

This section describes the execution of the first set of interviews. The interview environment, the process, and the pool of students are considered.

5.2.1 *Interview Environment*

As addressed in Section 3.2.2.1, the interviews were conducted via Zoom. Due to the restriction of the COVID-19 pandemic, personal interviews were not possible. Zoom offers the possibility of having

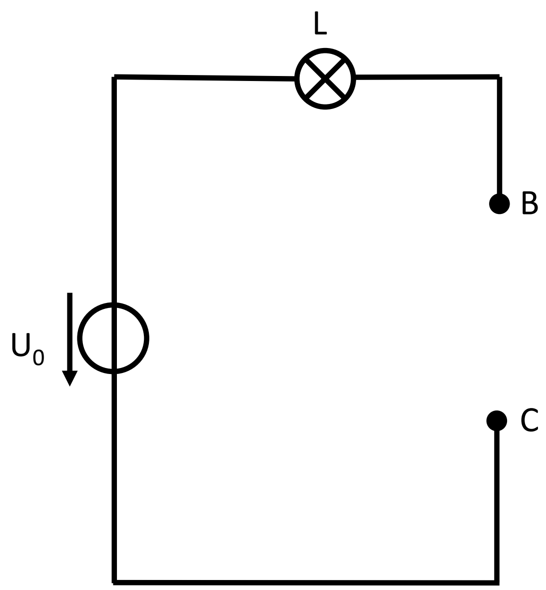


Figure 5: Second variation of the second interview circuit of the first set of interviews.

interviews with audio and video. Hence, creating an environment as close to the favored face-to-face as possible. Moreover, Zoom offers a whiteboard. Therefore, students can write down or draw their ideas into the circuits.

The interviews were recorded to analyze them at a later point. The recording offers the advantage that no one has to log the interview. The students were asked at the beginning of the interview if they agree to the recording. Moreover, a backup camera was used to record the interviewer's display, for the case that the recording via Zoom did not work.

5.2.2 *Interview Process*

All interviews were conducted between the end of November and the end of December 2020. The topic of electrical circuits had previously been taught in the lecture *Electrical Engineering I*.

After the student signed up for the interview, they received a Zoom-Link. On the day of the interview, the student was first asked about their permission to record the interview. Afterward, an introduction round ensued. If not already answered by the student in their introduction, the student was asked the following meta-questions:

- What are you studying?
- Did you previously take the exam in Electrical Engineering I?
- Do you have previous knowledge in electrical engineering?
- Do you have any hobbies related to electrical engineering?

- What is your final school grade?
- Do you like the course Electrical Engineering I?

Table 9 in Appendix A gives an overview of the students' answers to the meta-questions.

The student was informed that the interview is independent of their performance in the course *Electrical Engineering* and that their Professor will not see their interview. The student was told that they will receive the solutions at the end of the interview. Further, the student was reminded to think aloud during the entire interview, and that their thoughts of the topics were more important than answering the questions correctly.

Then, the student was asked the main questions to the first interview circuit, as described in Section 5.1.1. Depending on the student's answers, follow-up questions ensued, as described in Section 5.1.2. The order of the follow-up questions varied for each student and the interview situation. The goal of the interview was to obtain a deep insight into the students' understanding. Thus, asking a follow-up question after a specific main question could help in understanding the students' thoughts better.

After the first interview circuit, the student was asked the main questions to the second circuit. Again, follow-up questions ensued.

The same procedure was applied to the other circuits as well. However, not all circuits were presented to each student. The circuits that were presented to the student depended on the student's answers and the time. As described in Section 5.1.1, the different circuits offer different advantages and can be used to ask about different misconceptions in detail.

In the end, the student was informed about the correct answers and had the possibility to ask questions. The student was thanked and asked not to talk about the interview questions to other students.

After the interview, the recorded videos were saved, and notes and ideas regarding the interview were written down.

5.2.3 *Pool of Students*

The students that were interviewed in the first set of interviews were students from the studies electrical engineering, general engineering science, mechatronics, computer science, data science, as well as one student who did an orientation semester. Table 9 in Appendix A lists all students, their studies, their final school grade, and whether or not they had any background knowledge. Further, the table depicts in which chapters and sections the students are mentioned.

5.3 ANALYSIS OF THE FIRST SET OF INTERVIEWS

As described in Section 3.2.2.1, the interviews are analyzed based on the recorded videos.

The interviews are analyzed based on the following three research questions:

RQ1: Can the proposed misconception be confirmed?

RQ2: Can students have more than one misconception?

RQ3: How often do the different misconceptions occur?

In the first step, descriptions are extracted from the interviews. Based on the descriptions, similar ideas from different students are summarized. The ideas are analyzed in detail to extract the mental models of the students. The mental models are then compared to prior research results. Moreover, mental models are used to characterize the misconceptions. To convey the students' understanding as precisely as possible, students' quotes are used.

In order for the reader to follow the preparation of the second interview, the key results of the first interview are briefly summarized. The in-depth analysis is given in Chapter 7 and Chapter 8. The misconceptions that were observed in the first interview are listed below:

- Voltage/current confusion
- Kirchhoff's voltage law does not apply to open circuits
- Voltage is a substance that moves in the circuit
- Incorrect application of Ohm's law
- Incorrect assumption about the resistance of the open switch
- The Voltage is a global property in the circuit
- Voltage/electrical potential confusion
- Local reasoning

6 SECOND SET OF INTERVIEWS

The goal of the second set of interviews was to investigate how the students' understanding has changed over the expanded lecture time. Therefore, the following research questions were analyzed:

RQ4: Do students have the same misconceptions as in the first interview?

RQ5: Do students have other misconceptions than in the first interview?

This chapter explains the preparation, execution, and analysis of the second set of interviews.

6.1 PREPARATION OF THE SECOND SET OF INTERVIEWS

The preparation of the second set of interviews is explained in this section. The main questions, the follow-up questions, the question order, and the students that participated in the interviews are investigated in separate subsections.

6.1.1 *Main Questions*

Besides the circuits of the first set of interviews, which were used in the second set of interviews as well, two new circuits were designed. Both of the new circuits have a variation.

The first circuit that was designed for the second set of interviews is illustrated in Figure 6. The circuit is similar to the third circuit of the first set of interviews, as illustrated in Figure 3. However, the open switch does not exist in the circuit of the second set of interviews. Instead, points C and D are connected by a wire.

The circuit can be used to test if the students think that voltage and current always appear together or if they only think so for the open circuit and not for the short circuit.

The student was told the wire between C and D gets damaged and breaks. Hence, the circuit is open between points C and D. The new circuit is illustrated in Figure 7.

Although the variation of the first circuit of the second set of interviews (Figure 7) and the third circuit of the first set of interviews (Figure 3) ask about the same open circuit voltage, the student might not recognize the circuit from the first circuit because of the torn cable

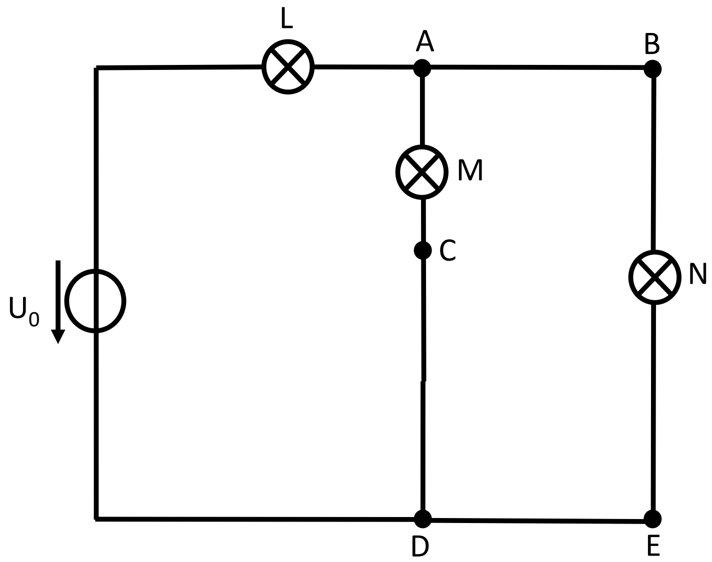


Figure 6: First interview circuit of the second set of interviews.

instead of the open switch. Therefore, the student might not remember their answers in the first interview. If the students' answer in the second set of interviews varies from their answer in the first set of interviews, it could either be related to the element of the torn wire or to the time in between the two sets of interviews.

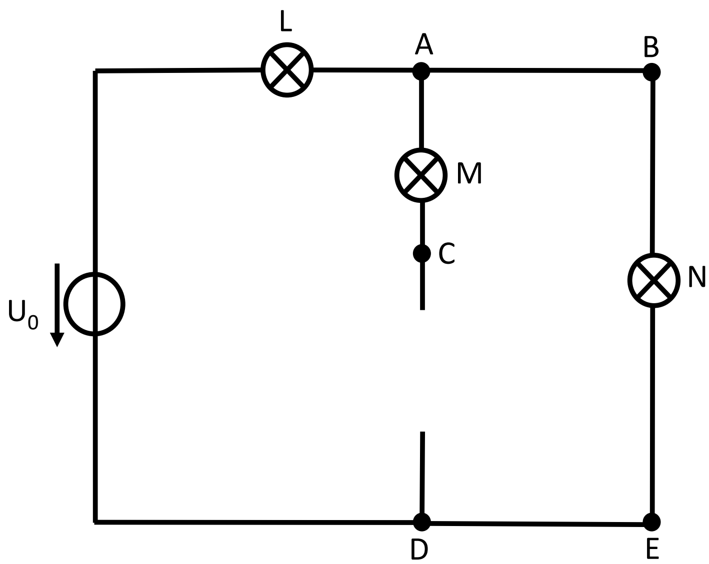


Figure 7: Variation of the first interview circuit of the second set of interviews.

The second circuit of the second set of interviews, in Figure 8, contains a series connection of two voltage sources, two bulbs, and an open switch. The voltage across the open switch is zero.

While the previous circuits asked about an open switch voltage that is bigger than zero, the voltage across the open switch in this circuit is zero. Therefore, the circuit can be used to test if the student learned the tasks related to the open switch by heart and does not understand the underlying concept. However, it needs to be considered that the series connection of voltage sources can be a cause of misconceptions as well, as analyzed by Smith and van Kampen (2011).

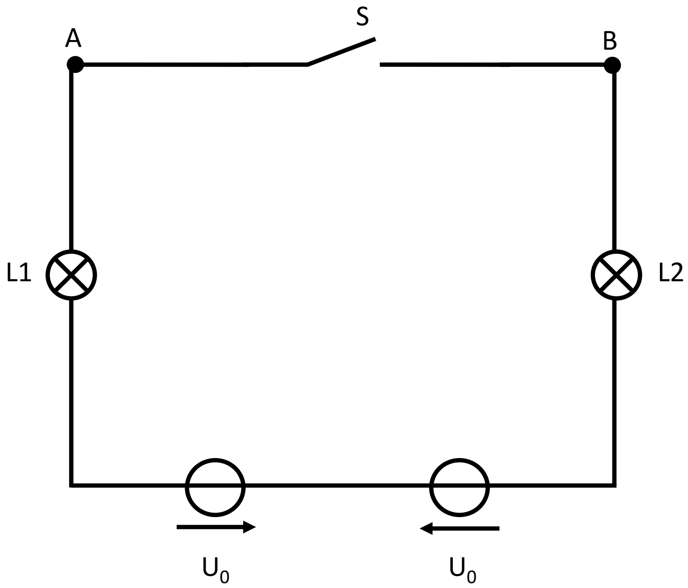


Figure 8: Second interview circuit of the second set of interviews.

Circuit Figure 9, in contrast to circuit Figure 8, contains only one voltage source. Therefore, the voltage across the open switch is the same as the voltage of the voltage source.

Comparing the second circuit of the second set of interviews with its variation makes it possible to test if the student understood the concept of the open switch or only learned an answer for a question that is related to the open switch by heart.

For each circuit main questions with fixed formulation were prepared. The main questions are listed in Table 5.

6.1.2 *Follow-Up Questions*

Based on the students' answers, the interview develops into different situations. For the different misconceptions, follow-up questions were prepared. Not all follow-up questions are used for each student.

All the misconceptions that were proposed in the literature were observed in the first set of interviews with the help of the prepared follow-up questions, as well. Therefore, the follow-up questions also serve as the basis for the second set of interviews. The follow-up questions are listed in Table 4.

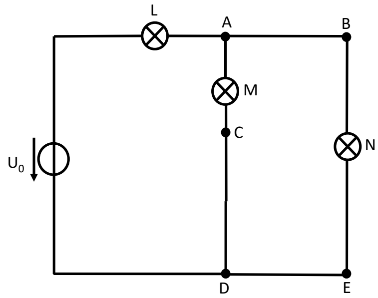
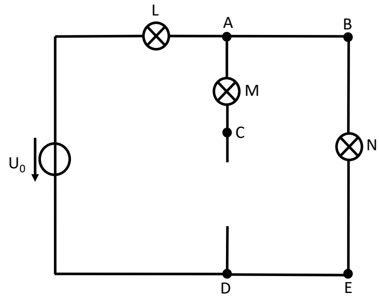
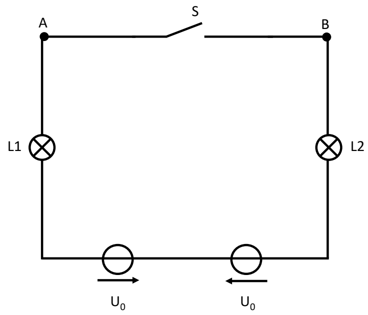
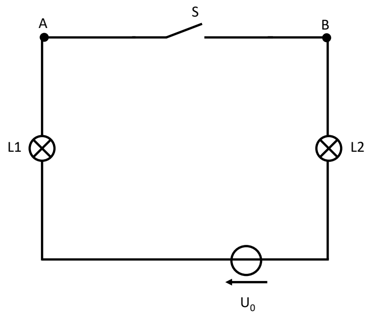
Circuit of the second set of interviews	Main questions
 Interview circuit 1 of the second set of interviews	- What is the voltage U_{DC}? Why? - What is the voltage U_{AC}? Why? - What is the voltage U_{AD}? Why? - What is the voltage U_{BE}? Why? - Which bulbs are lit? Why?
 Variation of the interview circuit 1 of the second set of interviews	- What is the voltage U_{DC}? Why? - What is the voltage U_{AC}? Why? - What is the voltage U_{AD}? Why? - What is the voltage U_{BE}? Why? - Which bulbs are lit? Why?
 Interview circuit 2 of the second set of interviews	- What is the voltage U_{AB}? Why? - Which bulbs are lit? Why?
 Variation of the interview circuit 2 of the second set of interviews	- What is the voltage U_{AB}? Why? - Which bulbs are lit? Why?

Table 5: Main interview questions for all circuits of the second set of interviews.

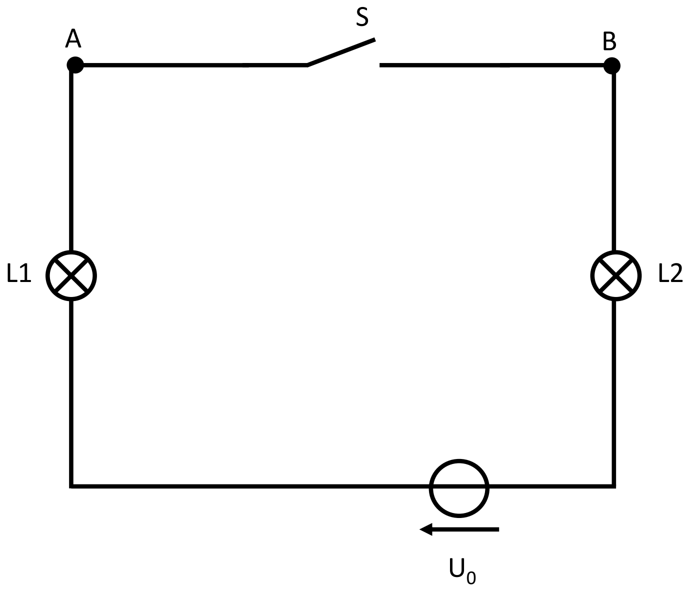


Figure 9: Variation of the second interview circuit of the second set of interviews.

The analysis of the first set of interviews shows that further misconceptions were observed in the interviews. Based on the misconceptions that were observed in the first interview, additional follow-up questions were prepared. Those follow-up questions are listed in Table 6.

6.1.3 *Question Order*

The goal of the second set of interviews was to investigate how the student's understanding has changed in comparison to their understanding in the first set of interviews. For this reason, the student's first interview was rewatched, and their key ideas were written down. The idea was to compare the student's understanding in the second interview to their previous understanding during the second interview. Thus, the follow-up questions could be adapted to investigate why and how the student's understanding has changed.

First, the student was again asked about one of the first three circuits of the first set of interviews, which are illustrated in Figure 1, Figure 2 or Figure 3. The student was asked if they still remember what they said or thought about the circuit in the first interview.

If the student remembered their thoughts and repeated them similarly, they were asked if they still thought the same way.

If the student still thought the same way about the circuit, the interview was used to gain a deeper understanding of the student's thoughts, as well as to observed new misconceptions. The new cir-

Misconception	Interview follow-up questions
Kirchhoff's Voltage Law does not apply to open circuits	- Asking the student to draw all the possible loops into the circuit. - Asking the student to write down KVL. - Why is it not possible to draw a loop along the open switch? - Is KVL valid? What are the requirements?
Incorrect assumptions about the resistance of the open switch	- What is the resistance of the open switch? - What is the resistance of the closed switch? - Why does the open switch not have any reistance?
The voltage is a global property in the circuit	- Asking about the voltage at different points of the circuit. - Asking the student to write down KVL. - Is KVL valid? - Why is the voltage everywhere the same? - What conditions would cause the voltage to be zero / to increase / to decrease?
Voltage/electrical potential confusion	- Asking about the voltage at different points of the circuit. - Asking the student about the voltage between two points? - What is the difference between these two kinds of voltage?
Local reasoning	- Why does the bulb lights up shortly? - Asking the student about the voltage between two points? - Asking the student to draw the voltage into the circuit. - Asking the student to draw the voltage into the circuit.

Table 6: Additional interview follow-up questions for the second set of interviews based on misconceptions that were observed in the first set of interviews.

cuits and follow-up questions were used, as described in Section 6.1.1 and Section 6.1.2.

However, if the student did not think the same way about the circuit anymore, they were asked to explain their new understanding. The main questions and follow-up questions were used to see if the student might have another misconception that was not previously observed. The main and follow-up questions are described in Section 6.1.1 and Section 6.1.2. Furthermore, the student was asked to explain how and why their understanding changed.

If the student did not remember their thoughts in the first interview, they were asked about the open switch voltage. Their answers were compared to their answers in the first interview.

If the student still had the same incorrect ideas, the interview was used to get a deeper understanding of the student's thoughts, as well as to observed new misconceptions. The main question and follow-up questions were used, as described in Section 6.1.1 and Section 6.1.2.

If the student's new and old ideas were different from another, the student was told about their ideas in the first interview. The student was asked if they remember why their thoughts changed. Further, the main and follow-up questions were used to see if the student might have another misconception that was not previously observed. The main and follow-up questions are described in Section 6.1.1 and Section 6.1.2.

6.1.4 *Student Recruitment*

10 out of the 20 students that participated in the first set of interviews were asked to participate in the second set of interviews as well. The students were contacted by e-mail at the end of January 2021. The 10 students were chosen to cover all the misconceptions that were observed in the first set of interviews.

5 out of the 10 students agreed to the second interview. The students that participated in the second interview are listed in Table 9 in Appendix A.

The students were individually asked by e-mail to participate in the second interview. Thus, the students were approached and asked about the second set of interviews on a more personal level. The e-mail, and the translation, that asks the students to participate in the second set can be found in Appendix A.

6.2 EXECUTION OF THE SECOND SET OF INTERVIEWS

Similar to the first set of interviews, the interviews were conducted via Zoom, due to the restriction of the COVID-19 pandemic. The Zoom environment for the interviews is described in detail for the first interview, Section 5.2.1.

The interviews of the second set of interviews were conducted in the last two semester weeks. In the time between the first and the second interview, the students were taught about electromagnetic fields in the lecture *Electrical Engineering I*.

The process of the second set of interviews was similar to the process of the first set of interviews, as described in Section 5.2.2. However, the specific questions, as well as the order of the questions of the second set of interviews, were described in the preparation of the second interview Section 6.1.

The students that were interviewed in the second set of interviews were from the pool of the first set of interviews. Therefore, all students in the second set of interviews were enrolled in the course *Electrical Engineering I*. The students that were interviewed in the second set of interviews are studying electrical engineering, general engineering, mechatronics, and data science. The students that participated in the second set of interviews are listed in Table 9 in Appendix A.

6.3 ANALYSIS OF THE SECOND SET OF INTERVIEWS

As described in Section 3.2.2.1, the interviews are analyzed based on the recorded videos.

The goal of the second set of interviews is to analyze whether the students' understanding changed between the two interviews. As described in Section 5.2.2, the first interview was conducted within the first third of the semester, while the second interview was conducted in the last lecture week, as described in Section 6.2. During this time, the lecture taught the students electromagnetic fields. The second set of interviews is used to test if the expanded lecture time and the topic of electromagnetic fields influence the students' understanding.

For this reason, the second set of interviews is analyzed based on the following two research questions:

RQ4: Do students have the same misconceptions as in the first interview?

RQ5: Do students have other misconceptions than in the first interview?

The questions are answered for each student individually in Chapter 7 and Chapter 8.

Moreover, the interviews of the second set of interviews were analyzed similar to the interviews of the first set of interviews, as described in Section 5.3. Descriptions from different students with similar ideas are summarized. The ideas are analyzed to extract mental models which are used to characterize the misconceptions and are compared to prior researches.

Part III

STUDENT MISCONCEPTIONS

7 STUDENT MISCONCEPTIONS REGARDING THE OPEN SWITCH

In this chapter, the students' misconceptions regarding the open switch are discussed. The misconceptions in this chapter either have a direct influence on the correct answer regarding the voltage or resistance of the open switch or are directly caused by the open switch questions. Hence, the misconceptions in this chapter were only observed due to the open switch or open circuit in the interview circuits.

In the interviews, the following misconceptions were observed:

- Voltage/current confusion
- Kirchhoff's voltage law does not apply to open circuits
- Voltage is a substance that moves in the circuit
- Incorrect application of Ohm's law
- Incorrect assumption about the resistance of the open switch
- The Voltage is a global property in the circuit
- Voltage/electrical potential confusion
- Local reasoning

The interviews were analyzed based on the five research questions, as described in Section 5.3 and Section 6.3. This chapter discusses the observed misconceptions individually. Studies that previously discussed or proposed the misconceptions are introduced. Further, the misconceptions are explained, narrowed down, and characterized with the use of student quotes.

7.1 VOLTAGE/CURRENT CONFUSION

The misconception of voltage/current confusion was described in the literature, as well as it was observed in the students' interviews in this work. In the literature a categorization was suggested by Engelhardt (1997, p.93). She states that students' assumptions about voltage/current confusion can be analyzed as one of the following three categories:

- Voltage and Current always appear together

- Voltage is a property of Current
- Voltage is caused by Current

Goris (2012, p.164) describes the same categorization based on her observations.

Engelhardt categorization is used as subcategorization in this work as well. The literature references and the student's statements in the interviews are specified and analyzed in each subsection, respectively.

7.1.1 *Voltage and Current Always Appear Together*

This misconception is described as one of three students' misconceptions in understanding voltage and current by Engelhardt (1997, p.93) and Goris (2012, p.164). Further, Timmermann (2020, p.150-151) describes it as one misconception that caused the students to incorrectly assume that the voltage across the open switch is zero. This incorrect assumption was observed in the interviews as well.

Student 10 is also mentioned in Section 8.3

Student 10 states in their first interview that they "think all the time in current,"[1] and calls it "useless."[2] In their first interview, the student does not further elaborate on this statement. However, in their second interview, the student further describes their understanding of voltage and current, with the following quote:

> I have always seen voltage and current together and never apart, if one is missing, the other is missing too.[3] (Student 10)

The student clearly states that they assume that the voltage and the current always appear together. To further elaborate this statement, the student uses the water analogy, as the following quotes indicate:

> The water can only flow if it is on top of the mountain. And then there must always be a potential for it so that the water flows.[4] (Student10)

> If water flows, a potential must have pre-existed, so that it can flow.[5] (Student 10)

1 German original: "[Ich] denke die ganze Zeit in Strom,"
2 German original: "[...] das bringt ja nichts."
3 German original: "Ich habe schon immer Spannung und Strom zusammen gesehen und nie auseinander. Wenn das eine nicht ist, ist das andere nicht."
4 German original: "Das Wasser kann ja nur fließen, wenn es oben auf dem Berg ist. Und dann muss dafür immer ein Potential da sein, damit das Wasser fließt."
5 German original: "Wenn Wasser fließt, muss vorher ein Potential geherrscht haben, damit es fließen kann."

In the student's use of the water analogy, the water represents the current. The height difference, the potential difference, represents the voltage. The student assumes that water can only flow when it is on top of the mountain and flows down. Thus, current can only flow when a voltage pre-existed.

Furthermore, the student describes why they assume that voltage cannot exist without current, either. They state that they "make a reversible reaction"[6] and conlude that "if no current flows, no voltage can drop."[7]

Student 10 clearly states that they assume voltage and current to always appear together. Further, they elaborate their understanding of both dependencies, as described above. The student explains this way of thinking and the use of the water analogy in their second interview and states that it is still their "first impulse"[8], even though they know that it is incorrect. While the student is aware of this misconception in the second interview, they have not overcome it yet, as it is still their "first impulse".

In the case of Student 10, the water analogy caused a misconception in the student's understanding. Besides the water analogy, the student names other analogies as well, such as the 'voltage-current-resitance-cartoon'. In the cartoon, three manikins are illustrated. The manikin that is labeled as 'voltage' is pushing the manikin 'current' through a wire, while the manikin 'Ohm' is cording the wire with a rope.

The student explains that for the other analogies, they conclude the same as for the water analogy, namely that "no current flows and therefore there is no voltage."[9] While the analogies helped the student with resistive elements, such as the bulbs, they caused difficulties in understanding elements for which the voltage and the current are not proportional, such as the open switch.

Moreover, some students assume that the voltage and the current are substances that move in the circuit. The students apply the same reasoning to both substances. Hence, in their mental models' voltage and current always appear together, as both are bound to the same conditions. However, as the students' primary misconception is that voltage is a substance that moves in the circuit, their statements are analyzed in Section 7.3. Those students are not analyzed in this section as well.

6 German original: "[Ich] mach eine reversibe Reaktion [daraus]."
7 German original: "Wenn kein Strom fließt kann keine Spannung abfallen."
8 German original: "erster Impuls"
9 German original: "Es fließt kein Strom und deshalb gibt es auch keine Spannung"

7.1.2 *Voltage is a Property of Current*

This misconception was first proposed by von Rhöneck (1982) who explained that a property cannot exist without a carrier. Therefore, voltage cannot exist without current. Further, von Rhöneck (2008) elaborated that students do not develop an independent voltage concept but rather see voltage as a concept, which is related to current. Engelhardt (1997, p.93) says that students mistake voltage as a property of current. She categorizes it as one out of three misconceptions of a voltage/current confusion. Goris (2012, p.164) uses the same categorization as Engelhardt. Timmermann (2020, p.150-151) further explicates this misconception by giving two examples, in which voltage is seen as the speed of or the force on electrons.

Student 1 is also mentioned in Section 7.3

Student 16 is also mentioned in Section 7.1.3, Section 8.3

Students 1 and 16 describe the voltage as a property of current, as the following quotes indicate:

> Voltage is the force that moves the electrons in a circuit.[10] (Student 1)

> The current is the charge carriers, which move in a specific amount of time through the wire and the voltage is how much energy these charge carriers have.[11] (Student 16)

Student 1 describes the voltage as the force that moves the electrons, while Student 16 describes the voltage as the energy of the charge carriers. The force and energy are described as properties of the electrons and charge carriers, respectively. Hence, the voltage is described as a property of the current.

If the voltage is described as a property of the current by students, it means that the voltage characterizes the current and is not an independent concept. Therefore, the voltage is only defined at points where a current exists.

The force and the energy are used to further characterize the electrons and the charge carriers. Since voltage is defined as the force or energy, it logically cannot exists without the electrons or charge carriers. In the students' mental models the voltage is not defined where no current exists. This aligns with their statements about the voltage across the open switch, as they both assume it to be zero.

Both student's statements can be categorized in the misconception of understanding voltage to be a property of current.

Student 16's understanding that voltage is the energy of the charge carriers could also be analyzed as a separate misconception. The

---

10 German original: "Spannung ist ja die Kraft, die die Elektronen im Stromkreis bewegt."

11 German original: "Der Strom ist ja die Ladungsträger, die in einer bestimmten Zeit durch den Leiter fließen und die Spannung ist halt welche Energie diese Ladungsträger haben."

authors von Rhöneck (1982) and McDermott and van Zee (1985) describe an energy/voltage confusion. However, both authors state that an energy/current confusion is more common than an energy/-voltage confusion, and that it is common for students to use the terms “current”, “energy”, “power”, “potential difference” and “voltage” interchangeably. After explaining their understanding of voltage and energy, Student 16 uses the terms “voltage” and “energy” interchangeably throughout the rest of the interview, as well. Therefore, it was refrained from analyzing Student 16 based on the voltage/energy misconception in this work. Further, another statement of Student 16 is analyzed in Section 7.1.3.

7.1.3 *Voltage is Caused by Current*

This misconception was first observed by von Rhöneck (1982). Engelhardt (1997, p.93) proposed this misconception as one of three misconceptions that students face as a voltage/current confusion. Goris (2012, p.164) made the same observation as Engelhardt. Timmermann (2020, p.152) provided students' interview answers to support this misconception. The idea of this misconception is that the current produces a voltage. Therefore, the voltage cannot exists in a circuit where there is no current. However, the voltage can exist at points where there is no current, as long as the current circulates in the circuit at all.

Students 16 and 19 made statements in the interviews that can be categorized in this misconception. The two students used different approaches to explain their thoughts. For this reason, the students are analyzed individually.

Student 16 is also mentioned in Section 7.1.2, Section 8.3

As described in Section 7.1.2, Student 16 understands the voltage as a property of current, as they describe the voltage to be the energy of charge carriers. After explaining their understanding of voltage, the student uses the terms “energy” and “voltage” interchangeably. For the case of the open switch, the student states that the voltage is zero since the charge carriers do not have any energy, as the following quote indicates:

> If I have no charge carriers at point B [at the open switch], I can't see how much energy they have. The energy of these things [the charge carriers] would be zero because they do not move because there are none there [at the open switch].[12] (Student 16)

The student states that the energy of the charge carriers is zero as long as they do not move. As the student uses the term “energy” to

12 German original: “Wenn ich keine Ladungsträger an Punkt B [am offenen Schalter] habe, kann ich auch nicht gucken wie viel Energie sie haben. Die Energie von diesen Dingern [die Ladungsträger] würde null sein, weil sie sich nicht bewegen, weil dort ja auch gar keine sind.”

describe the voltage, one can interpret that the student relates the existence of the voltage to the moving of the charge carriers. Therefore, the voltage is produced by moving charge carriers. As the student describes the charge carriers as the current, in the student's mental model the voltage is caused by the current.

The student uses a double "because" in their statement. This double use of "because" can be interpreted in two different ways. Those different interpretation possibilities are shortly discussed, and the chosen interpretation of this work is given. As described in Section 7.1.2, the student uses the words "voltage" and "energy" interchangeably. To keep the discussion comprehensive, the discussion below only refers to the "voltage".

On the one hand, the student might have used the second "because" unintentionally. The student could have only used it to back up their first thought that the charge carriers cannot move as long as they do not exist. In this case, both "because" describes the student's assumption that the voltage is caused by moving charge carriers, hence, the current.

On the other hand, is it possible that the student used the second because to convey a different thought within the same sentence. They could have assumed that the voltage cannot exist because the charge carriers do not move and that the voltage cannot exist because the charge carriers do not exist. In this case, the first "because" describes the student's assumption that the voltage is caused by the current, while the second "because" describes that the student understands the voltage to be a property of the current. The second "because" could describe that voltage can only exist if charge carriers exist. Hence, voltage is not an independent concept, instead, it characterizes the current. Therefore, the second "because" could describe the student's understanding that voltage is a property of current.

Even if the first interpretation is chosen for the double "because", Student 16 still holds both misconceptions, assuming that the voltage is caused by current and understanding the voltage as a property of current. The student made another statement within their interview that is categorized in the misconception of understanding voltage as a property of current, as analyzed in Section 7.1.2. Therefore, it is clear that Student 16 holds both misconceptions. In the student's mental model both misconceptions exist. Therefore, it is likely that they were both conveyed in the student's statement, which is analyzed above, as well. For this reason, the second interpretation possibility of the double "because" is chosen in this work, as it emphasizes that the student holds both misconceptions.

Student 19 is also mentioned in Section 7.2, Section 7.4 and Section 7.5

Another student that assumes that the voltage is caused by the current is Student 19. The student assumes that a potential difference depends on the protons, as the following quotes indicate:

> If there [branch without current] is no current flowing at all, then there are no protons arriving at C. There are none at D either. It means that there [at the open switch] is a voltage of zero. The electrical potential in C and D is the same.[13] (Student 19)

> It means here, in the middle [branch without current], would be no electrical potential because the protons just don't go there.[14] (Student 19)

Student 19 states that if the switch is open, no protons will go into the branch of the open switch. The student explains that a voltage would drop across the open switch if a potential difference exists between points C and D. Further, the student assumes that an electrical potential at point C exists if protons are at point C. Otherwise, the potential of C and D are the same, and no potential difference exists. Since the student assumes that no protons move into the branch of the open switch, they conclude that no potential difference exists between C and D. Therefore, no voltage drops across the open switch.

In their second interview, Student 19 explains their understanding in the first interview, as the following quotes indicate:

The second interview of Student 19 is analyzed in detail in *Section 7.5*

> I thought that there [across the open switch] was no voltage because I assumed that the current had an effect on whether there was a voltage or not. And I thought that if there is no current flowing, there can be no voltage.[15] (Student 19)

The student talked about the first interview question and confirmed that in their understanding the voltage depends on the current. When the student was asked if they remember why they thought that the current affects the voltage, they answered:

> I thought that it was because of these charge-particles that would flow.[16] (Student 19)

The student confirms that they coupled the existing of voltage to the charge carriers. Even though the student did not completely remember their understanding in the first interview, they confirmed that the categorization of voltage being caused by current can be applied to the student's understanding.

13 German original: "Wenn hier [Ast ohne Strom] gar kein Strom fließt, dann sind hier in C auch gar keine Protonen, die dort ankommen. In D sind eh keine. Das heißt dann hat man eine Spannung von null. Das Potential in C und D ist gleich."

14 German original: "Das heißt hier in der Mitte [Ast ohne Strom] wäre kein Potential, weil die Protonen gar nicht dahin kommen."

15 German original: "Ich glaube ich dachte, dass [über dem offenen Schalter] keine Spannung abfällt, weil ich davon ausgegangen bin, dass der Strom einen Einfluss hat ob es eine Spannung gibt oder nicht. Und ich dachte, dass wenn hier kein Strom fließt, es dort auch keine Spannung geben kann."

16 German original: "Ich glaube mit diesen Teilchen, die dann hier lang fließen würden, hab ich das gedacht."

7.2 KIRCHHOFF'S VOLTAGE LAW DOES NOT APPLY TO OPEN CIRCUITS

Another misconception that was observed in the interviews is characterized by the assumption that the KVL only applies to closed circuits or circuits in which a current is running. This misconception was not found in the literature inquiry.[17]

Students 7, 17, and 19 hold this misconception. All of them used different reasoning to explain their misconception. Those different approaches are shortly introduced.

Student 17 is also mentioned in Section 7.4

Student 17 explains that the KVL can only be applied to closed loops, as the following quotes indicate.

> A loop is defined by the fact that I have a closed loop within a network. And since my switch is open, it's not a closed loop, and, therefore, you can't apply the KVL rule.[18] (Student 17)

> The KVL describes a closed loop.[19] (Student 17)

Student 17 clearly states that KVL only applies to closed circuits.

While talking about the second circuit of the first set of interviews, the student only draws the loop along the bulb N, as depicted in Figure 10.

The student explains that it is not possible to draw a loop along the open switch since no voltage drops across the open switch, as the following quote indicates:

> I don't have a voltage dropping there [in the branch with the open switch], and, therefore, I don't get to the sum of zero [when the KVL is applied to the other two loops].[20] (Student 17)

As described in Section 7.4, Student 17 also has the misconception of prioritizing the current when applying Ohm's law. Based on that misconception, the student assumes that the voltage across the open switch is zero. Further, based on the incorrect assumption that the

17 The inquiry was performed by searching scholar.google.de, ieee.org, per-central.org, peer.asee.org, as well as the intern bibliographical database of the Engineering Education Research Group at TUHH using different combinations of the search terms "(student) misconception", "KVL/loop rule/mesh rule/Kirchhoff's rule/law", "closed loop/closed mesh", "current (dependency)" in English as well as in German.

18 German original: "Eine Masche ist ja dadurch definiert, dass ich eben einen geschlossenen Umlauf habe, innerhalb eines Netzwerkes. Und da mein Schalter aber offen ist, ist es kein geschlossener Umlauf und daher kann man die Maschenregel nicht anwenden."

19 German original: "Na, die Masche beschreibt einen geschlossenen Umlauf."

20 German original: "Ich habe keine Spannung, die da [im Zweig mit dem offenen Schalter] abfällt und ich dadurch nicht auf die Summe null komme [wenn die Maschengleichung auf die anderen zwei Maschen angewendet wird]."

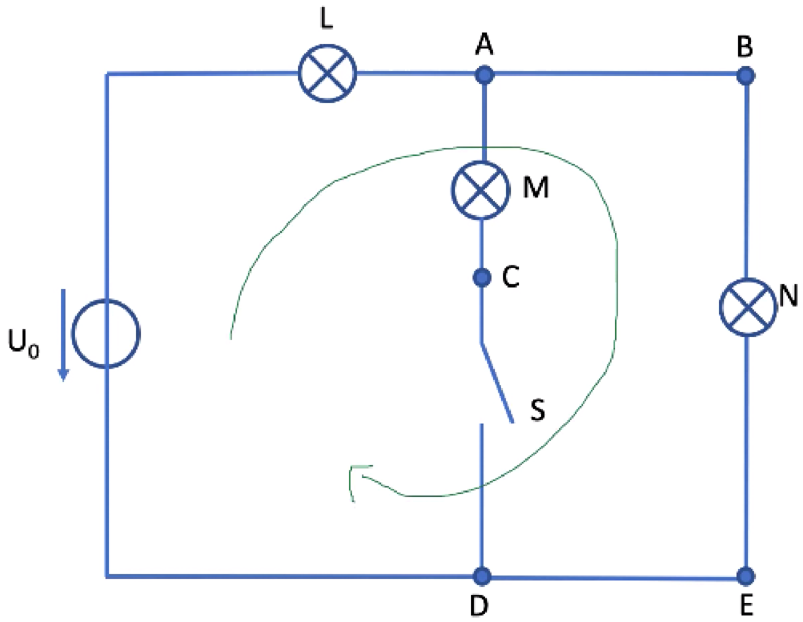


Figure 10: Student 17's drawing of Kirchhoff's Voltage Law in the second interview circuit of the first set of interviews.

voltage of the open switch is zero, the student states that the KVL does not apply to the loops along the open switch. Thus, when applying the KVL, it would be incorrect.

However, earlier during the interview, the student stated that the voltage across the open switch is the same as the voltage across bulb N. Hence, the branch with the open switch has a voltage that is bigger than zero. When the student was confronted with their contradiction, they express their concern:

> But we don't have a loop... Ok, that means it [the voltage across the open switch] is zero?[21] (Student 17)

The student understands their contradiction and gets insecure about their answer. In the end, the student questioned their prior, correct statements instead of questioning their misconception about KVL. However, their final answer is unsure and doubtful.

Further, Students 7 and 19 also incorrectly assume that KVL can only be applied to closed loops or loops in which a current is running. In contrast to Student 17, this misconception did not cause an incorrect assumption about the open switch voltage in their answers.

Student 7 correctly states the voltage across the open switch by arguing with the potential difference and the electrical potential. Nevertheless, the student makes several statements in which they explain that the KVL cannot be applied to an open circuit, as the following quotes indicate:

21 German original: "Wir haben aber keine Masche... Ok, das heißt es [die Spannung über dem offenen Schalter] ist null?"

> If it [the switch] is closed, you can also draw a loop here [along the switch]. If it [the switch] is open, this loop makes no sense.[22] (Student 7)

> This loop [loop along the open switch] would not be a closed loop, and, therefore, would not give me correct results.[23] (Student 7)

> You can only use loops in a correct way if you have a closed circle.[24] (Student 7)

The student states that KVL cannot be applied to open loops and that an application of KVL to an open loop would cause incorrect results. However, the student does not further specify or explain these statements.

Further, the student states that "one calls it also a loop circle, which means the current can flow once around."[25] This statement suggests that the student might refer the application of KVL to the condition that a current runs in the loop. Whether the student refers the application of KVL to the condition of a loop being closed or to the condition of current running in a loop is not clear. Either way, the student holds the misconception of incorrectly assuming that the KVL cannot be applied to open circuits.

During the debriefing of the interview, the student calls the loop along the open switch a "pseudo loop"[26]. Although the student was told the correct approach to apply the KVL, they still do not understand a loop along an open switch as the same as a loop along the closed switch. This misconception is strongly held in the student's mental model.

As described in Section 3.1.1, Posner et al. defines the existing knowledge and concepts as the conceptual ecology. New observation can either align or contradict with the conceptual ecology. In the case that the new observations contradict the conceptual ecology, an anomaly happens. In case of an anomaly, the student either changes their conceptual ecology so that the new observation aligns with the existing knowledge, or the student does not change their conceptual ecology, in which case a misconception occurs. Further, Posner et al. describes different ways of responses of students that do not contain a change of the conceptual ecology.

22 German original: "Wenn er [der Schalter] geschlossen ist, kann man auch hier [am Schalter entlang] eine Masche einzeichnen. Wenn er [der Schalter] offen ist, ergibt diese Masche keinen Sinn."

23 German original: "Diese Masche [Masche am offenen Schalter entlang] wäre keine geschlossene Masche und würde mir deshalb keine richtigen Ergebnisse liefern."

24 German original: "Man kann Maschen nur sinnvoll einsetzten, wenn ein geschlossener Kreis vorliegt."

25 German original: "Man nennt es ja auch Maschenumlauf, dass heißt der Strom kann einmal rund herum fließen."

26 German original: "Pseudomasche"

Student 7's response to the debriefing makes a good example for applying the theoretical background of the conceptual change theory, described by Posner et al.. The student was told the solution in the debriefing of the interview. While the student might understand the correct idea in the future, their first response was to not change their concept ecology. Instead, the student tries to force the new information into their concept ecology, without actually changing the concept ecology, as the student calls a loop along an open circuit a "pseudo loop".

In comparison to Student 17, Student 7's misconception is stronger held but does not influence their assumption about the open switch voltage.

Student 19 is also mentioned in Section 7.1, Section 7.4 and Section 7.5

Student 19's approach to this misconception is different from the approaches of Students 7 and 17. Student 19 tries to use a proof by contradiction to explain that the application of KVL is invalid for an open circuit. The student correctly states the voltage across the open switch by referring to the potential difference and by comparing the open switch voltage to the terminal voltage of an ideal voltage source.

The student several times mentions the KVL and states that "if it [the switch] was closed now, then you could draw in a loop."[27] When the student was asked if it is possible to apply the KVL to the open circuit, they negated it. The student then applied KVL to the open circuit as a proof of contradiction. The student uses their previous acquired result for the open switch voltage, which they correctly state to be U_0, and set the loop equation

$$U_q - U_0 - U_M - U_L = 0 \tag{1}$$

with U_q being the source voltage, U_0 being the voltage across the open switch, and U_M and U_L being the bulb voltages. Further, the student states that the voltages across the bulb, U_M and U_L, are zero. As a result, the student concludes that

$$U_q = U_0 \tag{2}$$

Although the student correctly applies the KVL to the open circuit, they still argue that KVL does not apply to the open circuit. But instead of explaining why they assume that KVL cannot be applied to open circuits, even though they received the correct results by doing so, they switched their argumentation towards a comparison to an ideal voltage source.

In the student mental's model KVL cannot be applied to open circuits. Although the student correctly applied KVL to the loop with the open switch, they refuse to link their approach and equations

27 German original: "Wenn er [der Schalter] jetzt hier geschlossen wäre, dann könnte man eine Masche einzeichnen."

with KVL. Further, the student tries to avoid explaining this contradiction by changing their explanation towards a comparison to an ideal voltage source. Dealing with their misconception is too difficult or uncomfortable for the student.

All of the above-mentioned students state in different ways that KVL cannot be applied to open circuits or circuits in which no current is running. Even contradictions in their explanation or the correct solution did not cause them to question their misconception. This observation is especially striking since all of the three students at least once mentioned correct ideas or approaches to solve the voltage across the open switch. Further, two of the students settled for the correct answer about the voltage across the open switch. Nevertheless, neither of them questioned the misconception of applying KVL only to closed loops or loops in which a current is running, and all of them hold this misconception throughout the whole interview.

7.3 VOLTAGE IS A SUBSTANCE THAT MOVES IN THE CIRCUIT

This misconception was described by von Rhöneck (1982), Goris (2012, p.164), who conducted interviews with questions from the DIRECT, and Timmermann (2020, p.152), who enhanced the findings by providing further students' quotes from interviews, using the DIRECT's questions among others. All authors describe that students understand the voltage as a substance or matter that moves/circulates/flows through the circuit. They further distinguish the misconception between the case in which voltage does not start moving because of the open switch and the case in which voltage moves out of the open switch.

In the interviews, it was observed that students who have this misconception use different approaches to explain their understanding. Those different approaches are shortly introduced. Further, it was observed that the incorrect understanding of voltage being a substance that moves through the circuit causes further incorrect implications in the student mental models. Those incorrect implications are analyzed as well.

7.3.1 *Different Approaches that Lead to the Misconception of Understanding Voltage as a Substance that Moves in the Circuit*

In the interview questions, three different approaches were observed. All of those approaches express the students' understanding of assuming voltage to be a substance that moves through the circuit. The three approaches, such as

- Approach 1: Voltage converges at the Electrical Grounding
- Approach 2: The "Voltage Potential"

- Approach 3: No Current, no Voltage

are presented in the following.

APPROACH 1: VOLTAGE CONVERGES AT THE ELECTRICAL GROUNDING Student 15 drew a loop (brown) and an electrical grounding (red) into the first circuit of the first set of interviews to explain their understanding of voltage, as illustrated in Figure 11.

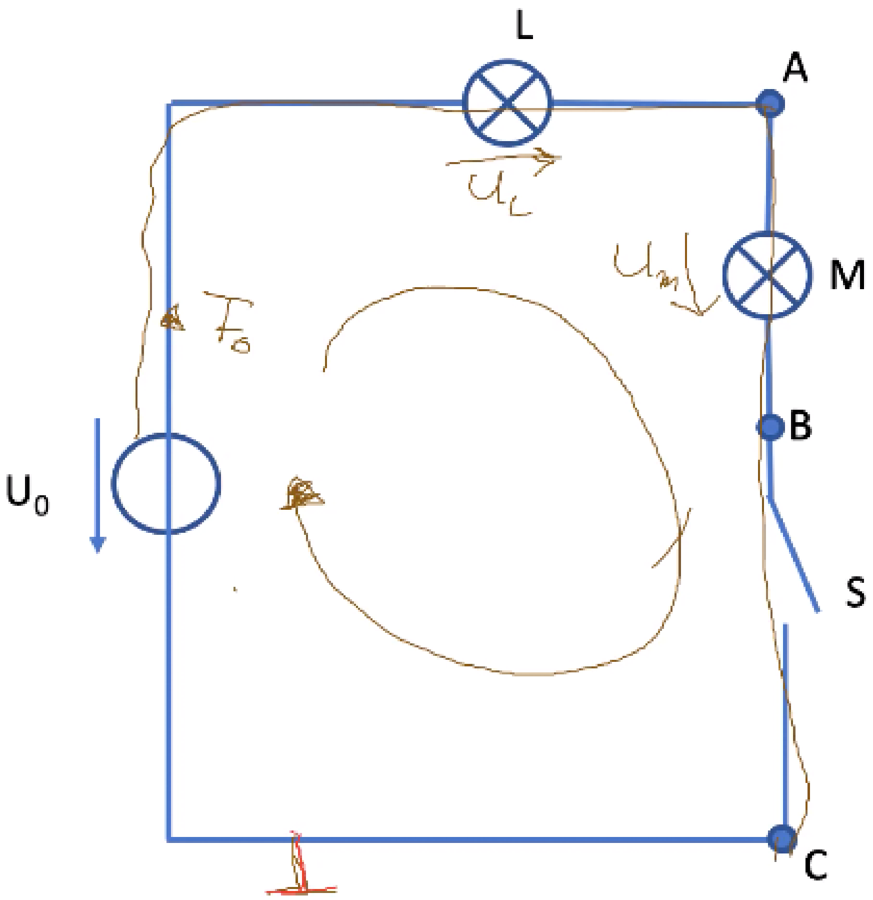


Figure 11: Student 15's description of voltage in the first circuit of the first set of interviews. The loop is depicted in brown, the electrical grounding in red.

In the student's mental model, voltage is a substance that moves in the circuit and "converges" at the electrical grounding, as the following quote for the case of the closed loop indicates:

> If we now draw our potential (red) down here, which means we set our zero point, then the voltage will sort of runs down, converge and become zero.[28] (Student 15)

28 German original: "Wenn wir jetzt hier unten unser Potential einzeichnen, also unseren Nullpunkt setzten, dann wird die Spannung hier unten quasi zusammenlaufen und zu null werden."

The student explains that the voltage "runs" through the circuit. Hence, the student understands voltage as a substance that moves through the circuit. Further, the student understands the electrical grounding as a point where the voltage becomes zero.

For the case of the open switch, the student states that the voltage is zero, as the following quotes indicate:

> The circuit is open. Therefore, I think that here [in the circuit] cannot be any voltage.[29] (Student 15)

> Since the circuit is not closed, we no longer have any voltage.[30] (Student 15)

The student argues that as long as the switch is open, no voltage is in the circuit at all. In the student's mental model, an open circuit hinders the voltage to start "running" through the circuit. As a result, as long as the switch is open, Student 15 assumes that no voltage is running through the circuit at all.

Student 1 is also mentioned in *Section 7.1*

APPROACH 2: THE VOLTAGE POTENTIAL In the second approach, the term "voltage potential" is used by students. The "voltage potential" is no correct concept in electrical engineering. Nevertheless, two students independently used this incorrect concept to describe their understanding. Students 1 and 8 describe that even though a "voltage potential" exists, no voltage is "circulating" in the circuit, as the following quotes indicate:

> There is a voltage potential, but since the circuit is not closed, the voltage cannot circulate.[31] (Student 1)

> There is a voltage potential, but at the moment, there is no voltage between the points.[32] (Student 8)

Both students describe a "voltage potential", which is a concept that does not exist in electrical engineering. Two different interpretation possibilities are shortly introduced. On the one hand, it is possible that they mistook the electrical potential as the "voltage potential". On the other hand, they might have mixed up voltage and electrical potential and made up an entirely new concept. However, taking a closer look at their explanation, the "voltage potential" does

29 German original: "Der Schaltkreis ist eben unterbrochen. Deswegen glaube ich, dass hier [im Schaltkreis] keine Spannung sein kann."

30 German original: "Weil der Schaltkreis nicht geschlossen ist haben wir keine Spannung mehr."

31 German original: "Es herrscht ein Spannungspotential, aber da der Stromkreis nicht geschlossen ist, fliesst da halt keine Spannung."

32 German original: "Da besteht zwar ein Spannungspotential, aber im Moment zwischen den Punkten ist keine Spannung."

not cause a voltage, or at least not if the voltage cannot circulate. Therefore, the second interpretation seems more likely.

Both of the students assume that the voltage is a substance that moves through the circuit. For Student 1, this explicitly shows in their quote, by the word "circulates". Student 8 used the words "flow" and "run" to describe the voltage during their interview.

APPROACH 3: NO CURRENT, NO VOLTAGE Three students used a third approach, in which they drew a comparison to the current to explain why they assume the voltage across the open switch is zero. Students 11, 13, and 20 state that no voltage flows through the circuit since no current flows either.

Student 20 uses the resistance of the open switch to explain their thoughts:

> Here [at the open switch] we have infinite resistance because air works as an insulator. Therefore, the current does not flow through U_{BC}. And, therefore, no voltage flows through U_{BC}, either.[33] (Student 20)

With U_{BC} being the voltage across the open switch. The student argues that the current does not flow in the circuit since the resistance of the open switch is infinite. Further, the student states that the same applies to the voltage, as it cannot flow through the circuit either. The student uses the word "flow" to describe the voltage, as the student understands the voltage to be a substance that moves through the circuit. Further, the student uses the current to explain their understanding, as the student assumes both the voltage and the current to be substances that move in the circuit. Therefore, the students draw the same conclusions for the current and the voltage. The student explains that as long as the switch is open, neither can flow.

In their second interview, the student still has the misconception of voltage being a substance that moves in the circuit. The student states that

> I still think similarly to how I did back then: The voltage [across the open switch] is zero.[34] (Student 20)

The student assumes that their answers in the first interview were correct and that the voltage across the open switch is zero. To explain their statement, Student 20 uses the words "run" and "flow" to describe the voltage in the second interview as well.

Students 11 and 13 made similar statements, such as

Student 11 is also mentioned in *Section 7.4*

33 German original: "Hier [am offenen Schalter] haben wir ja einen unendlichen Widerstand, dadurch, dass Luft als Isolator wirkt. Dadurch fliesst der Strom nicht durch U_{BC}. Und dadurch fliesst hier auch keine Spannung durch U_{BC}."

34 German original: "Ich denke immer noch ähnlich wie damals: Die Spannung [über dem offenen Schalter] ist null."

> "The voltage moves through the entire circuit, as does the current."[35] (Student 11)

and

> "When there is no current flowing, there is no voltage flowing accordingly."[36] (Student 13)

Students 11 and 13 both use the words "moves" and "flows" that imply that the voltage is a substance that runs through the circuit. Further, both of them draw a connection to the current, stating that neither the voltage nor the current can flow in the circuit if the switch is open.

The students understand voltage to be a substance that moves through the circuit. Further, all of them describe current as a substance as well. As a consequence, the same properties apply to current and voltage; as long as the circuit is open, neither can flow. Therefore, one can argue that those students hold the misconception of the voltage/current confusion, as described in Section 7.1. However, in comparison to the misconception of the voltage/current confusion, the students use terms like "flow" and "move", which imply that the students understand the voltage as a substance that flows in the circuit. Therefore, the students' statements are not additionally analyzed as a voltage/current confusion (Section 7.1).

7.3.2 *Incorrect Implications Resulting from the Misconception of Voltage Being a Substance that Moves in the Circuit*

The misconception of voltage being a substance that moves through the circuit causes incorrect implications in the students' mental models, such as:

- Voltage Consumptions
- Incorrect Application of Kirchhoff's Laws.

VOLTAGE CONSUMPTION Most of the students who describe the voltage as a substance that moves through the circuit attach importance to the direction of the voltage. While some students draw the voltage direction as opposed to the voltage arrow of the voltage source, some draw it alike. Especially for the case of the closed switch, the case in which the voltage can flow through the circuit in the students' mental models, the direction of the voltage gained special importance. Students 8 and 11 argued that the voltage is "reduced" by the internal resistances of the bulbs, as the following quotes indicate:

35 German original: "Die Spannung geht ja einmal durch den ganzen Stromkreis durch, wie der Strom ja auch."

36 German original: "Wenn kein Strom fliesst, fliesst dementsprechend auch keine Spannung."

> "The voltage is a little bit reduced by L and M."[37] (Student 8)

and

> "The voltage is reduced at the internal resistances of the bulbs."[38] (Student 11)

In their mental model, the voltage is a substance that moves through the circuit and gets "reduced" by passing resistances, such as the internal resistances of the bulbs. As a consequence, the voltage that moves back to the voltage source is smaller than the voltage that moves out of the voltage source.

This misconception of voltage consumption was also observed by Goris (2012, p.163), but not explicitly connected to the misconception of voltage being a substance that moves in the circuit.

INCORRECT APPLICATION OF KIRCHHOFF'S CURRENT LAW In the interviews, it was observed that two students who assumed the voltage to be a substance that moves in the circuit applied the Kirchhoff's Current Law (KCL) to the voltage. The quotes of Students 11 and 13 show that the student assumed that the voltage splits up at the nodes:

> One can now argue with the node rule [KCL]: Here [lower node] the voltage or the current should split up, but this does not work because the circuit is not closed.[39] (Student 11)

> When it [the switch] is closed, the voltage would divide equally between the two loops.[40] (Student 13)

Both students assume that the voltage is a substance that moves in the circuit and that the voltage splits up at the nodes. The students use the terms "split up" and "divide", which emphasize that they apply KCL to the voltage. Student 11 even states that they apply KCL.

While Student 11 talks about the case of the open switch, Student 13 talks about the closed switch. Student 13 argues that the voltage splits equally at the node, as they assume the internal resistances of the bulb to be the same.

37 German original: "An L und M fällt ja so ein bisschen Spannung ab."

38 German original: "Die Spannung verliert quasi an den Innenwiderständen der Lampen."

39 German original: "Man kann jetzt mit der Knotenregel argumentieren: Hier [lower node] müsste sich ja die Spannung oder der Strom aufteilen. Das funktioniert nur nicht, weil der Stromkreis nicht geschlossen ist."

40 German original: "Wenn er [der Schalter] geschlossen ist, würde sich die Spannung gleich zwischen den beiden Maschen aufteilen."

In this section, the misconception of incorrectly applying KCL directly results from the incorrect understanding of assuming that voltage is a substance that moves in the circuit. In contrast, in Section 7.2, the incorrect application of KVL is investigated. The incorrect application of KVL was observed to be an independent misconceptions in the interviews.

7.4 INCORRECT APPLICATION OF OHM'S LAW TO OPEN CIRCUITS

The incorrect application of Ohm's law to the open switch was described by several authors, such as Hussain et al. (2012, p.468), Smaill et al. (2012), Skromme and Robinson (2015) and Timmermann (2020, p.153). The authors' analysis, as well as the students' responses in the interviews of this work, lay down two possible categories in which the incorrect application of Ohm's law can be distinguished.

Therefore, the categories

- Prioritizing the Current in Ohm's law
- Blind Reliance on Ohm's law

are suggested in this work to further categorize and analyze the incorrect application of Ohm's law. The literature references and the student's statements in the interviews are specified and analyzed in each subsection, respectively. Further, those categories could be considered as two misconceptions on their own.

7.4.1 *Prioritizing the Current in Ohm's Law*

Students who prioritize the current in Ohm's law first consider the values of the current and the resistance. However, when applying Ohm's law they prioritize the current and neglect the value of the resistance. It is clear that the understanding of Ohm's law is incorrect. Students who prioritize the current in Ohm's law most likely have misconceptions with the understanding of Ohm's law in general and not exclusively at the open switch. Nevertheless, in the interviews, this misconception was only observed while the students talked about the open switch voltage.

Hussain et al. (2012, p.468) describes an example in which a student specified the resistance of the open switch to be zero since no current is flowing across the open switch, but only considers the current when applying Ohm's law. The author states that students rely on Ohm's law but consider the current to be the prime concept.

Students 17 and 19 made statements in the interviews, in which they first mentioned the resistance of the open switch but prioritize the current when applying Ohm's law.

Student 17 assumed the resistance of the open switch to be infinite. While applying Ohm's law, they neglected this correct assumption. Instead, they prioritized the current, as the following quotes indicate:

Student 17 is also mentioned in Section 7.2

> For the open switch, I would say it [the resistance] is infinite because I have no connection.[41] (Student 17)

> There [at the open switch] is no voltage drop because there [at the open switch] is no current flow because voltage and current are always proportional to each other. And since I have no current flow, I would also have no voltage.[42] (Student 17)

> I [The current] is proportional to U. R is infinite because I have no electrical connection. I have no current flowing because I have no electrical connection. That would mean that my U is still zero because of this proportionality.[43] (Student 17)

Student 17 explains that the open switch has a resistance of infinite. Further, the student explains that the open switch prevents a current from running through the circuit. When applying Ohm's law, the student argues with the proportionality of current and voltage and states that the voltage is zero since the current is zero. Although the student mentioned the proportionality between current and voltage, the student does not mention the resistance, which defines this proportionality. Instead, Student 17 prioritizes the current while applying Ohm's law. As a consequence of this misconception, the student incorrectly concludes the voltage across the open switch to be zero.

Student 19 assumes that the resistance of the open switch is zero. However, when applying Ohm's law the student only refers to the current, as the following quotes indicates:

Student 19 is also mentioned in Section 7.1, Section 7.2 and Section 7.5

> "The resistance across CD [the open switch] is zero."[44] (Student 19)

> If no current flows here at all, with $U = R \cdot I$ and if $I = 0$, also $U = 0$.[45] (Student 19)

---

41 German original: "Beim offenen Schalter würde ich sagen ist er [der Widerstand] undenlich, weil ich keine Verbindung habe."

42 German original: "Es fällt keine Spannung da [am offenen Schalter] ab, weil ich da [am offenen Schalter] halt keinen Stromfluss habe, denn die Spannung und Strom sind immer proportional zueinander. Und da ich kein Stromfluss habe, würde ich auch keine Spannung anliegen haben."

43 German original: "I ist proportional zu U. R ist unendlich groß, weil ich keine leitende Verbindung habe. Ich habe keinen Strom der fließt, weil ich eben keine leitende Verbindung haben. Das würde ja bedeuten, dass mein U trotzdem immer noch null ist, aufgrund dieser Proportionalität."

44 German original: "Der Widerstand über CD ist null."

45 German original: "Wenn hier gar kein Strom fließt, mit $U = R \cdot I$ und wenn $I = 0$ ist, ist auch $U = 0$."

The student uses Ohm's law to explain why they assume the voltage across the open switch to be zero. Although the student prior specified the resistance of the open switch to be zero, they neglect their assumption of the resistance of the open switch when applying Ohm's law. Instead, the student prioritizes the current when applying Ohm's law.

One can argue that Student 19 did not mention the resistance of the open switch consciously, as they assumed it to be zero. However, the opposite can be said as well: The student could have neglected the current instead of the resistance, as they assumed it to be zero, as well. Since the student only referred to the current while applying Ohm's law, the interpretation of a current prioritization is justified.

While Student 17 assumes the resistance of the open switch to be infinite, Student 19 assumes it to be zero. Nevertheless, neither of them considers the resistance while applying Ohm's law. Both students prioritize the current while applying Ohm's law.

The second interview of Student 19 is analyzed in detail in Section 7.5

In their second interview, both students correctly apply Ohm's law during the interview. Further, both students correctly answer the questions regarding the open switch in the second interview.

7.4.2 *Blind Reliance on Ohm's Law*

Smaill et al. (2012) and Skromme and Robinson (2015) describe the incorrect application of Ohm's law as a "naïve application of Ohm's law" and a "blind reliance on Ohm's law". Both authors describe that students argue that the current across the open switch is zero. Therefore, the voltage is assumed to be zero as well. The students neglect the consideration of the resistance of the open switch completely.

In the misconception's category of prioritizing the current in Ohm's law, the students did not neglect the resistance. Instead, they thought about the resistance but prioritized the current when applying Ohm's law. In the naïve application of Ohm's law, the students do not consider the resistance of the open switch at all. Instead, they blindly rely on Ohm's law.

Student 11 is also mentioned in Section 7.3

Student 3 and 11 used a blind reliance on Ohm's law to argue that the voltage across the open switch is zero, as the following quotes indicate:

> According to Ohm's law, $U = R \cdot I$ and I is zero, and, therefore, U is also zero.[46] (Student 3)

> There is definitely no current flowing. And if there is no current, there can be no voltage, according to Ohm's law.[47] (Student 11)

46 German original: "Nach dem Ohm'schen Gesetz ist $U = R \cdot I$ und I ist null und dadurch ist U auch null."

47 German original: "Es fließt definitiv kein Strom. Und wenn es kein Strom gibt, kann es ja eigentlich auch keine Spannung geben, nach dem Ohm'schen Gesetz."

Both students used Ohm's law to argue that the voltage across the open switch is zero. They did not question whether an application of Ohm's law to the open switch is possible. Neither did they question the resistance of the open switch. Instead, they blindly rely on Ohm's law.

When Student 11 was asked about the resistance of the open switch, they answered that "the resistance doesn't matter if there is no current."[48] The student does not consider the resistance of the open switch at all, and naïvely denies the importance of the resistance when specifically asked about it.

7.5 INCORRECT ASSUMPTION ABOUT THE RESISTANCE OF THE OPEN SWITCH

In the interviews, it was observed that two students incorrectly assume the resistance of the open switch to be zero. This surprising misconception was not described in any comparable work in the literature.[49]

For the case of the open switch, Students 9 and 19 made statements about the resistance of the open switch to be zero, causing incorrect assumptions about the voltage across the open switch, as the following quotes indicate:

Student 9 is also mentioned in Section 8.1
Student 19 is also mentioned in Section 7.1, Section 7.2, Section 7.4

> "A switch has no resistance, so there should not be any voltage."[50] (Student 9)

> "The resistance across CD [the open switch] is zero."[51] (Student 19)

Student 9 states that a switch has no resistance and concludes that, for this reason, no voltage drops across the open switch. This statement can be interpreted in two different ways. On the one hand, the student could have implied that the voltage across the open switch is zero. On the other hand, the student could have assumed the voltage across the open switch to be undefined. Since the student did not further specify their understanding of the voltage across the open switch in their interview, no certain interpretation can be given. Regardless of the interpretation, the student's misconception of assuming the resistance of the open switch to be zero causes an incorrect assumption about the voltage of the open switch.

48 German original: "Der Widerstand ist ja egal, wenn es kein Strom gibt."
49 An inquiry was performed by searching scholar.google.de, ieee.org, per-central.org, peer.asee.org, as well as the intern bibliographical database of the Engineering Education Research Group at TUHH using different combinations of the search terms "(student) misconception", "open switch/circuit", "Ohm's law" and "(electrical) resistance" in English as well as in German.
50 German original: "Ein Schalter hat keinen Widerstand, deswegen müsste da eigentlich keine Spannung herrschen."
51 German original: "Der Widerstand über CD ist null."

Student 19 states that the resistance of the open switch is zero. While, the student did not make any immediate, direct conclusion about the voltage across the open switch, they later used the voltage divider in the interview. Applying the voltage divider, Student 19 concludes that the voltage across the open switch is zero. The misconception of assuming the resistance of the open switch to be zero causes an incorrect answer for the open switch voltage.

Further, both students state that "there is no resistance when the switch is closed"[52] While the students assume the same resistance for the case of the open and closed switch, they do not presume the same for the current. On the one hand, both of the students state that "no current flows"[53] "if the circuit is open."[54] For the case of the closed switch, on the other hand, both students assume the current to be larger than zero. Therefore, this misconception only relates to an incorrect understanding of the open switch resistance. The students are not able to differentiate between the resistance of the open and closed switch.

Student 9 does not explain why they assume the resistance of both, the open and closed switch, to be both zero. Instead, they were confident in their statement. Therefore, an explanation for this misconception cannot be given for Student 9.

Student 19, in contrast to Student 9, wonders "if it is realistic that there is no voltage drop in U_{CD} [voltage across the open switch]."[55] Regardless of their doubts, the student does not question their assumption for the resistance of the open switch and sticks to their conclusion that the voltage across the open switch is zero.

Student 19 further has the misconception of assuming that the voltage is produced by current, Section 7.1.3, of applying the KVL only if a current is running in the loop, Section 7.2, and of prioritizing the current while applying Ohm's law Section 7.4.1. All of those misconceptions include a connection or dependency of the current. Therefore, it might be possible that the misconception of assuming the resistance of the open switch to be zero relates to the current as well. A possible explanation that could be applied in this matter was described by von Rhöneck and Volker (1985), who says that students understand the resistance as a current consumption rather than a hindrance of current. An open switch would not be understood as a consumptive component. Thus, the student might neglect the resistance of the open switch entirely. Nevertheless, it is not possible to make a certain conclusion for Student 19 since the student did not explain their thought process of this misconception in detail during

52 German original: "Da ist kein Widerstand, wenn der Schalter offen ist."
53 German original: "[Es] fließt kein Strom."
54 German original: "Wenn der Stromkreis offen ist [...]."
55 German original: "[Ich frage mich] ob das realistisch ist, dass in U_{CD} [Spannung am offenen Schalter] keine Spannung abfällt."

the interview. Instead, a further investigation is required to make a reliable conclusion about this student's misconceptions.

In their second interview, Student 19 correctly answers all the questions about the open switch and correctly applies KVL to all interview circuits. In their second interview, the student does not assume that the current causes the voltage, they do not prioritize the current while applying Ohm's law, they do not assume the resistance of the open switch to be zero and the student applies the KVL for loops in which no current is running correctly. The student does not have any misconceptions with any questions regarding open circuits in their second interview.

As described in Section 3.1.1, Posner et al. defines the existing knowledge and concepts as the conceptual ecology. New observation can either align or contradict with the conceptual ecology. In the case that the new observations contradict the conceptual ecology, an anomaly happens. In case of an anomaly, the student either changes their conceptual ecology, so that the new observation aligns with the existing knowledge, or the student does not change their conceptual ecology, in which case a misconception occurs. The first case, changing the conceptual ecology for the new observation to align is called accommodation. It is not an easy or quick process for the student.

Student 19 gathered the new observations about the open switch in the debriefing of the first interview. The student explained that they worked on the topic of the open switch afterward and understood their misconceptions. Further, Student 19 correctly answers all the questions about the open switch in the second interview. Included in the second interview of Student 19 was the second circuit of the second set of interviews (Figure 8), in which the voltage across the open switch is zero. Therefore, and in combination with the correct reasoning of the student to each question it is safe to say that the student did not guess the answers or learned the answers about the open switch by heart. For this reason, is Student 19 a good example of the process of accommodation.

8

STUDENT MISCONCEPTIONS REGARDING THE GENERAL UNDERSTANDING OF VOLTAGE

In this chapter, misconceptions of students regarding the general understanding of voltage and electrical laws that were observed in the interviews are described. Those observations are not directly related to the student's incorrect explanation about the voltage across the open switch but rather to the student's general misconception of voltage or general electrical laws. Neither are the misconceptions in this section the primary cause for incorrect answers regarding the open switch voltage. Further, some students even answered correctly when asked about the open switch voltage, but hold misconceptions regarding the general voltage understanding, nonetheless.

The misconceptions regarding the general understanding of voltage that were observed in the interviews are listed below:

- The voltage is a global property in the circuit
- Voltage/electrical potential confusion
- Local reasoning

The misconceptions are analyzed and narrowed down individually in the following sections. Further, the misconceptions are characterized and described with the use of student quotes. Similar to the misconceptions in Chapter 7, the misconceptions are analyzed based on the five research questions which are described in Section 5.3 and Section 6.3. Moreover, the observed misconceptions are compared to misconceptions that were proposed in previous studies.

8.1 THE VOLTAGE IS A GLOBAL PROPERTY IN THE CIRCUIT

Two students misunderstand the voltage to be a global property in the circuit. In the literature inquiry, this misconception was not found.[1]

Student 9 states that they "have heard before that if a network is not connected on both sides, no current flows, but the voltage is still

Student 9 is also mentioned in Section 7.5

1 The inquiry was performed by searching scholar.google.de, ieee.org, per-central.org, peer.asee.org, as well as the intern bibliographical database of the Engineering Education Research Group at TUHH using different combinations of the search terms "(student) misconception", "physical understanding/qualities/meaning", "voltage" in English as well as in German.

available."[2] The student specifies that the voltage is available "at the bulbs."[3]

While the student's initial statement sounds correct, their specification explains their deeper, incorrect understanding. The student assumes that the voltage across the bulbs is the same for the case of the open switch and the case of the closed switch. The student assumes the voltage to be a global property that applies to all the loads no matter if the switch is open or closed.

Especially striking is that the student starts their statement by saying "I have heard before that [...]"[4]. It is possible that the student tries to align a statement, which they have heard before, but do not understand, with their strongly held misconception. The student tries to align that the voltage "is available" in an open circuit with their misconception of assuming the resistance of the open switch resistance to be zero, as described in Section 7.5.

The misconception of understanding voltage as a global property does not cause the student to incorrectly answer the voltage across the open switch. Instead, it is rather a misconception that refers to the general understanding of voltage.

Student 12, on the other hand, thinks that the voltage is the same at any point in the circuit, as the following quote indicates:

> In the entire circuit, U_0 would be the same at all points.[5]
> (Student 12)

Included in the student's explanation of "at all points" are the open switch, the bulbs, and any two points on the wire.

When the student was asked to draw the voltage into the first circuit of the first set of interviews, they simplified their voltage arrows into one big circle around the circuit, as depicted in Figure 12.

The student explains their drawing, stating that the voltage "is available in the complete circuit"[6] In Student 12's mental model, the voltage is a global property that is always and at any points available.

Further, the student states that for the case of the closed switch, nothing changes except that "the consumers would work, for example, the bulbs would light up"[7]. In the student's mental model, the global voltage is not influenced by opening or closing the switch. Instead, the student understands the voltage as a concept that is detached from other qualities in the circuit.

2 German original: "[Ich] habe schon mal gehört, dass sollte ein Netzwerk nicht an beiden Seiten verbunden sein, fließt kein Strom, aber die Spannung ist trotzdem verfügbar."
3 German original: "[...] an den Lampen."
4 German original: "Ich habe schon mal gehört [...]"
5 German original: "Im gesamten Stromkreis wäre U_0 an allen Stellen gleich."
6 German original: "[Die Spannung] ist im kompletten Schaltkreis vorhanden."
7 German original: "Die Verbraucher würden funktionieren, also Lampen zum Besipiel leuchten"

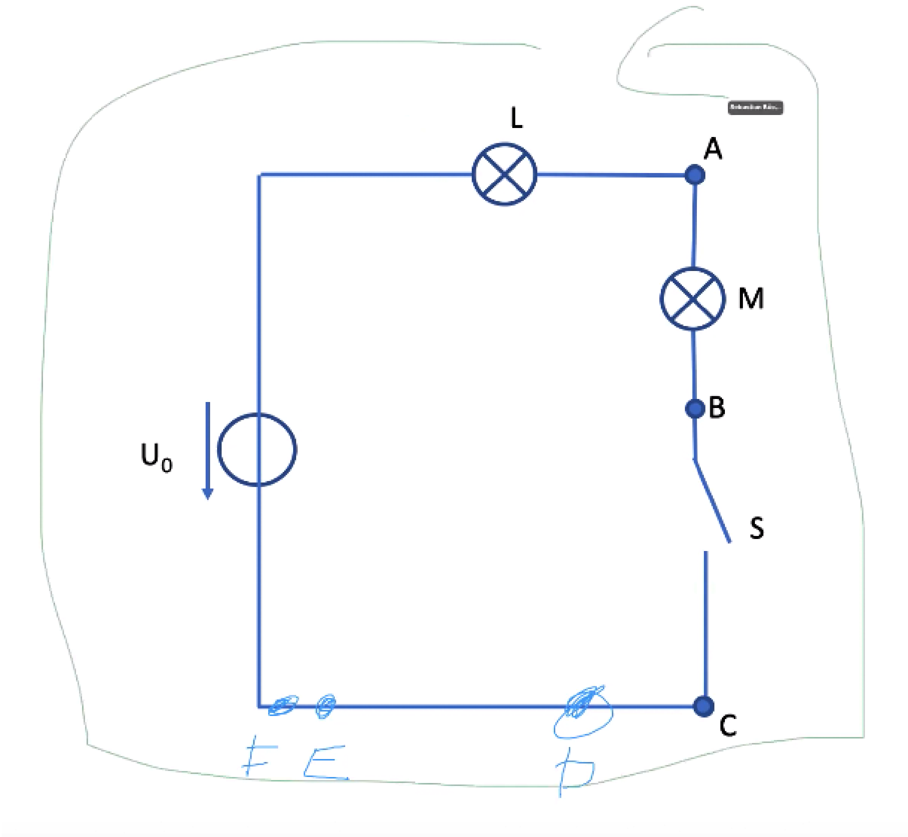


Figure 12: Student 12's description of voltage (green) in the first circuit of the first set of interviews.

Since the student assumes a global voltage in the whole circuit, they correctly answered the voltage of the open switch. Nevertheless, their understanding of voltage is still incorrect.

8.2 voltage/electrical potential confusion

As described by McDermott and Shaffer (1992), some students have the misconception of confusing the voltage and the electrical potential. McDermott and Shaffer describes that the students with this misconception pay more importance to the place of a bulb in the circuit rather than how the bulb is connected. Timmermann (2020, p.220) further specifies that this misconception can occur even without the student using the term "electrical potential".

Students with this misconception in the interviews assumed that the voltage is the same as the electrical potential. As a consequence, the students refer the voltage to single points in the circuit, the electrical potential, instead of the difference of two points, the potential difference.

Some textbooks, such as Schwarz and Oldham (1993, p.22) use the voltage symbol V for both the voltage and the electrical potential. Moreover, in the context of electronic circuit design, this nomenclature is often used as a simplification, as explained in Tietze et al. (2008, p.1500). However, the students are enrolled in a first-semester undergraduate course. Therefore, a confusion based on the notation in the context of electronic circuit design is unlikely.

All of the students with the misconception of voltage being a substance that moves through the circuit, Section 7.3, assumed the voltage to be at a local point in the circuit since they assume that the voltage runs through the circuit. Moreover, some of those students struggled with differentiating the terms "electrical potential" and "voltage". However, the students' primary misconception that leads to the incorrect answer about the voltage across the open switch is the misconception of understanding voltage as a substance. Therefore, those students are not individually listed in this misconception.

Another student who has the misconception of confusing the electrical potential and the voltage is Student 2. For the second circuit of the first set of interview (Figure 2), the student correctly states and explains that the voltage U_{BC}, the voltage across the open switch, equals the voltage U_{AD}, the voltage across bulb N. However, the student states that the voltage U_{AD} is the difference of the voltage U_A and U_D. Further, the student states that "U_A is the voltage with the resistance of L."[8] The student makes a similar statement for the voltage at point D. The student assumes that the voltage is a local quality that exists at the points A and D. Moreover, the student even uses the voltage divider to determine the voltage U_A and U_D. The use of the voltage divider clarifies that the student definitely understands U_A and U_D as voltages. Therefore, the option that the student only uses the voltage symbol while talking about the electrical potential, but understanding both concepts, nonetheless, is confuted.

Student 2 has two mental models of voltage that exist besides one another. On the one hand, the student describes the voltage to be at a local point, for example, at point A. This understanding of voltage is incorrect since it is actually the electrical potential the student is referring to. On the other hand, the student describes the voltage as a difference of two points, for example, U_{AD}. However, the student incorrectly assumes this difference to be a voltage difference instead of a potential difference.

While explaining the voltages U_A and U_{AD} the student expresses their doubts. However, the student does not come to the correct conclusion.

8 German original: "U_A ist ja die Spannung mit dem Widerstand L."

8.3 LOCAL REASONING

The misconception of local reasoning was described by Engelhardt (1997), McDermott and Shaffer (1992), McDermott and van Zee (1985) and Timmermann (2020, p.115,170). Students who use the approach of local reasoning do not have a holistic approach to the circuit but rather see the components of the circuit as individual parts that do not influence each other. Students 10 and 16 made statements during the interview that can be classified as local reasoning.

Student 16 uses local reasoning while explaining with the water analogy their understanding of voltage and current in the second interview. In the first interview, the misconception was not observed for the student.

Student 16 is also mentioned in *Section 7.1*

Student 16 explains that the water starts at the voltage source, moves downwards, gets narrowed because of the resistance of L, and stops at the switch, as the student understands the switch as a hatch.

Further, the student transmits their understanding of local reasoning to the electrical circuit, as the following quote indicates:

> The bulb would light up briefly at the beginning because electrons run through the bulb briefly at the beginning. The electrons run up to the switch and stop. But no electrons would follow because the circuit is not closed.[9] (Student 16)

Student 16 states that, depending on the voltage of the voltage source and the bulb parameter, the bulb would light up briefly. The student approaches the circuit locally. They assume that the bulb lights up briefly when the electrons pass it. In the student's mental model, the bulb would not glow permanently since the electrons are stopped at the open switch.

Similarly, Student 10, for parts of their first and second interview, uses the local reasoning to argue that the current runs through the bulbs, which light up shortly until the current is stopped at the open switch. Similar to Student 16, Student 10 uses the water analogy to explain their understanding, as well. For both students, the water analogy causes the misconception of local reasoning.

Student 10 is also mentioned in *Section 7.1*

Since the course *Electrical Engineering* is a first-semester undergraduate course, an understanding of transients, which are caused by the switch capacities, is not a reasonable explanation for the students' statements. Further, this DC-circuit implies a steady-state understanding. Therefore, the students' explanations can be analyzed as local reasoning.

9 German original: "Die Lampe würde am Anfang kurz leuchten, weil am Anfang kurz Elektronen durch die Lampe laufen. Die Elektronen laufen bis zum Schalter und stoppen da. Aber es kommen keine Elektronen nach, weil der Stromkreis ja nicht geschlossen ist."

Part IV

QUESTIONNAIRE

9 QUIZ DEVELOPMENT

For this work, a questionnaire for a quiz was developed. However, the quiz was not yet used to obtain student data. The goal of the quiz is to detect the student's misconceptions as accurately as possible. For this reason, a multi-tier MC SR quiz was developed. The quiz consists of four circuits. The quiz questions, as well as the order of the questions, are listed in Appendix B. This chapter explains the circuits, as well as the idea of the structure and the questions.

9.1 QUIZ STRUCTURE

The quiz is a MC SR multi-tier quiz. The first tier, the lead question of each circuit, asks about the voltage across the open switch. Hence, the lead question answers the question *if* the student understands the open switch correctly, as described in Section 3.2.3.3. The lead question's answer options are ensued by follow-up questions, the other tiers of the multi-tier quiz.

The following tiers are used to detect whether the student understands the concept of the open circuit correctly or to detect and narrow down the misconceptions that were observed in the interviews as precisely as possible. As explained in Chapter 7 and Chapter 8, some misconceptions were observed in more detail than others, based on the students' answers in the interviews. Therefore, some misconceptions can be investigated in more detail in the test, as well. As a result, some answer options of the lead question result in more tiers, the follow-up questions, than others.

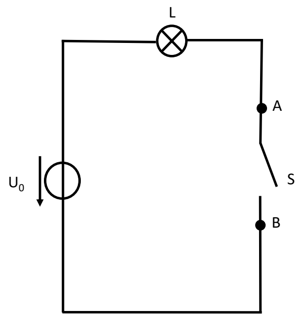
Further, the number of each follow-up question's answer options depends on the interview findings as well, as some misconceptions were observed in more detail.

Having a different number of follow-up questions, the tiers, for each answer option of the lead question and a different number of answer options in the MC SR questions makes this quiz inadequate for diagnostic analysis, as explained in Section 3.2.3.1 and Section 3.2.3.3.

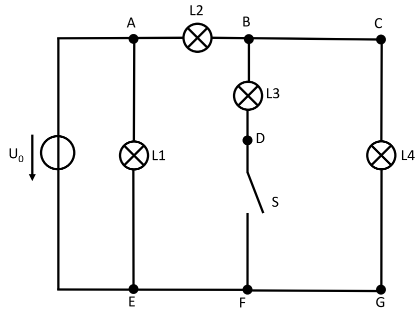
9.2 QUIZ CIRCUITS

In this section, the four quiz circuits are introduced. Further, their advantages and differences are shortly discussed.

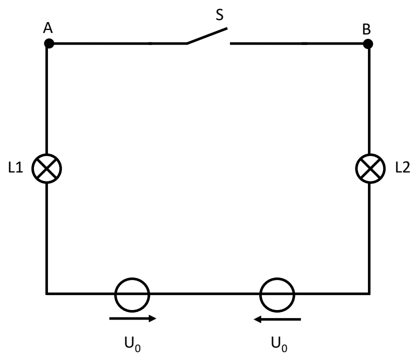
Table 7 illustrates the different circuits. For the first quiz circuit, the open switch voltage, U_{AB}, is equal to U_0, which is 12V. The open switch voltage of the second quiz circuit, U_{DF}, equals U_{CG}, which is between 0V and 12V. The open switch voltage of the third quiz circuit is U_{AB}, which is equal to 0V. The fourth quiz circuit has two open switches. The voltage across the first switch, S1, is U_{AB}, which is equal to 12V. The voltage across the second switch, S2, is U_{CD}, which is equal to 0V. The complete quiz assignments are illustrated in Section B.1.



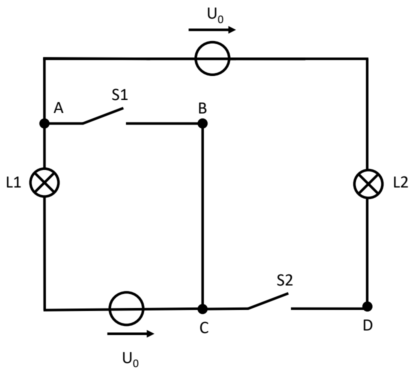
First quiz circuit



Second quiz circuit



Third quiz circuit



Fourth quiz circuit

Table 7: The four quiz circuits.

The four quiz circuits vary in complexity and the correct answer for the open switch voltage. This variety of circuits and correct answers ensures that the student does not guess the correct solution or learns a solution by heart.

The simplicity of the first quiz circuit, on the one hand, reduces incorrect answers that are caused by misconceptions that are not related to the open switch. The more complex circuits, on the other hand, make it harder for the student to guess the correct answer. In the second quiz circuit, the student needs to understand which bulb voltages need to be considered to determine the open switch voltage. Quiz circuits three and four both contain two voltage sources. A series connection of voltage sources can be a cause of misconceptions, as described by Meyer and Land (2003). Therefore, the level of difficulty is higher for the quiz circuit three and four. Further, quiz circuit four contains two open switches. Having two different correct answers for the voltages of the two open switches in the same circuit shows if the student can apply the correct electrical concepts when dealing with open switches or if they just learned answers about the open switch by heart. This last point is reinforced by the variety of the four circuits in general. Further, the variety of the circuits increases the possibility of detecting several misconceptions of one student.

9.3 QUIZ QUESTIONS

In this section, the idea of the quiz question development is explained. All the questions in the quiz are MC SR questions.

For all of the four circuits, the lead question in the quiz is to determine the open switch voltage U_{OS}. The letters "OS" stand for "Open Switch" and need to be substituted by the corresponding letters that label the open switch voltage in the corresponding circuit. The lead question is a MC SR question with three to five answer choices. The last two answer options only apply to circuits 3 and 4, as students might incorrectly apply the principle of superposition.

Question 1: What is the voltage U_{OS}?

1.1 $U_{OS} = 0V$

1.2 $0V < U_{OS} < 12V$

1.3 $U_{OS} = 12V$

1.4 $12V < U_{OS} < 24V$

1.5 $U_{OS} = 24V$

Depending on the chosen answer option, different MC SR follow-up questions ensue. Those follow-up questions are used to determine whether the student understood the concept of the open switch correctly and to detect and narrow down possible misconceptions of the student.

Based on the observed student misconceptions, as described in Chapter 7 and Chapter 8, the follow-up questions were designed. The follow-up questions were designed to cover as many misconceptions and their specifications as possible. This is a reasonable procedure, as all of the observed misconceptions in this work were held by several students. In the design process, the question formulation was chosen similar to the students' statements. Further, keywords that were used by the students were integrated into the formulation of the follow-up questions, as well. The follow-up questions for each circuit are listed in Section B.2. As the correct answer option for each circuit varies, the order of the follow-up question for each lead question varies as well. Further, not all follow-up questions can be applied to each circuit.

The quiz covers the following misconceptions and their specifications:

- Incorrect application of Ohm's law
- Incorrect assumption about the resistance of the open switch
- Voltage is a substance that moves in the circuit
  - Voltage flows out of the circuit
  - Voltage does not flow at all
  - Voltage does not flow into the open switch branch
  - Kirchhoff's current law applies to the voltage
- Kirchhoff's voltage law does not apply to open circuits
- Voltage/current confusion
  - Voltage and current always appear together
  - Voltage is caused by current
    - Moving charge carriers cause the voltage
    - Charge carriers cause the electrical potential
  - Voltage is a property of current
    - Voltage is the energy of the charge carriers
    - Voltage is the velocity of the charge carriers
    - Voltage is the force on the charge carriers
- The Voltage is a global property in the circuit
- Voltage/electrical potential confusion

Except for the misconception of *Local reasoning*, all the misconceptions that were observed in the interviews are covered in the questionnaire.

The question charts in Section B.3 illustrate the answer options and the order of the follow-up questions that leads to the possible misconceptions of the student. Further, the correct answer option is indicated in the question charts. As some misconceptions are observed in less detail than others, text fields are part of the quiz, as well. The student is asked to explain their thoughts or their answer in those text fields. The method of written student answers is explained in Section 3.2.2.3. The answer options that lead to text fields are marked in the question charts. Moreover, choosing the correct answer does not necessarily mean that the student understood the underlying concepts correctly. Therefore, the student is asked to explain their answer after picking the correct answer, as indicated in the question charts.

The misconceptions of *Incorrect Application of Ohm's Law* and *Incorrect Assumptions about the Resistance of the Open Switch*, as well as *Voltage is a Substance that Moves in the Circuit* and *Kirchhoff's Law Does Not Apply to Open Circuits*, can be detected besides one another in the quiz, as indicated in the question charts in Section B.3. For the other misconceptions, detection of several misconceptions of one student with only one circuit is not possible due to the single-response characteristic of the MC SR questions. However, the use of several circuits in the quiz increases the possibility of detecting several misconceptions of one student.

Part V

CONCLUSION

10 CONCLUSION

This chapter concludes the present work.

In the first section, the work and the results are summarized and concluded. Further, the work is reflected, and a perspective on future work is given in the following sections.

10.1 SUMMARY AND CONCLUSION

In this work, the understanding of voltage in the context of the open switch is investigated with students that are enrolled in the undergraduate course *Electrical Engineering I* at TUHH. Misconceptions regarding the open switch that were proposed in prior studies were analyzed in Chapter 4. Based on these proposed misconceptions, an interview guide was developed, as described in Section 5.1. Student interviews were conducted. The following questions were the basis of the analysis of the interviews:

RQ1: Can the proposed misconception be confirmed?

RQ2: Can students have more than one misconception?

RQ3: How often do the different misconceptions occur?

The interview analysis has shown that all misconceptions that were proposed in the literature were observed in the interviews of this work as well. Further, additional misconceptions were observed. Several students had more than one misconception. Moreover, all of the misconceptions that were observed in this work were held by more than one student.

After the first set of interviews, a second set of interviews was ensued. An interview guide for the second set of interviews was developed, as described in Section 6.1. The second set of interviews was used to answer the following research questions:

RQ4: Do students have the same misconceptions as in the first interview?

RQ5: Do students have other misconceptions than in the first interview?

In the analysis of the second set of interviews, the research questions were answered differently for each student. In comparison to

In this work observed misconception	Page
Current/Voltage confusion	p.45-51
Kirchhoff's Voltage Law does not apply to open circuit	p.52-56
Voltage is a substance that moves in the circuit	p.56-62
Incorrect application of Ohm's law	p.62-65
Incorrect assumption about the resistance of the open switch	p.65-67
The voltage is a global property in the circuit	p.69-71
Voltage/electrical potential confusion	p.71-72
Local reasoning	p.73

Table 8: Misconceptions that were observed in the student interviews in this work, and the pages where they are discussed.

the first interview of each student, some students held the same misconceptions, some held new misconceptions, and others held no misconceptions at all in their respective second interviews.

All research questions were answered in detail for each misconception in Chapter 7 and Chapter 8.

Based on the analysis of both set of interviews, the student misconceptions were investigated. Chapter 7 describes the misconceptions regarding the open switch. Chapter 8 describes misconceptions regarding the general understanding of voltage that were observed in the interviews. All of the misconceptions that were observed in this work are listed in Table 8. Further, Table 8 lists the pages on which each misconception is discussed in this work.

Furthermore, a questionnaire was developed in this work, as described in Chapter 9. For the questionnaire, MC SR multi-tier questions were used. The MC SR questions offer the advantage of a simplified quantitative analysis in comparison to interviews. The multi-tier questions were used to detect and narrow down the misconceptions as precisely as possible. The questionnaire that was developed in this work can be used as a base for a quiz. Most of the observed misconceptions are covered by the questionnaire.

The analysis of the interviews has shown that the open switch is a cause of difficulty for many students. The difficulties affect students of all levels and backgrounds and are not limited to students with weaker performances in their previous studies.

Further, this work has shown that the open switch is a good context for research to obtain an insight into the students' understanding of voltage. Moreover, the open switch should as well be used in teaching courses. The open switch can be used as an example to teach students that not all elements have a proportional relation of voltage and current or that voltage cannot always be determined from the current. Gaining this understanding early in their studies will help the students in later courses.

Furthermore, this work concludes that some analogies cause difficulties in student understanding. Recognizing that not all analogies are beneficial for the students' understanding, and instead identifying which analogies and which of their parts are helpful can improve teaching courses.

Moreover, students should learn through examples or tutorials that the KVL is independent of the current and can indeed be applied to open circuits. This might help students in their understanding of Kirchhoff's laws as well as their general understanding of voltage.

10.2 REFLECTION

The goal of this work was to analyze the students' understanding of voltage in the context of the open switch. Using interviews and analyzing them qualitatively was a good approach to gain a deep insight into the students' understanding. The interview duration, procedure, and analysis were appropriate and effective.

The expected interview duration was met for almost all interviews. The date of the interviews fitted well, as all students were familiar with the elements that were used in the circuit and the fundamental electrical concepts and laws. The interview questions helped in gaining a deep insight into the students' understanding. Further, the continuous update of the follow-up questions based on conducted interviews continuously improved the interviews. Moreover, the five research questions benefit the interview analysis since they cover a wide analysis range.

Based on the third research question RQ3, the interview analysis gives an approximate idea of the frequencies of the misconceptions. To answer the third research question more precisely, a questionnaire was developed. However, the questionnaire was not yet used to obtain student data. Nevertheless, the questionnaire can be used in future work to conduct a quiz that can be analyzed quantitatively.

The interviews were analyzed based on the definition of misconception by Hammer (1996), as described in Section 3.1.2. Hammer says in his definition that misconceptions are "strongly held, stable structures". However, in the interviews, it was observed that some students held several loose, incorrect ideas that were not connected with one another. While some students repeated the same ideas throughout the interview, others dropped one idea in favor of another. Therefore, the definition by Hammer might not be the best theoretical background for the analysis of those interviews. An analysis based on a different theoretical framework, for example, an investigation of the students' understanding based on the idea of the liminal space, as proposed in the threshold concept (Meyer and Land (2003)), might increase the outcome of the analysis.

10.3 FUTURE WORK

In this work a questionnaire was developed to detect students' misconceptions. However, the quiz was not yet given to students. Thus, based on the developed questionnaire in Chapter 9, a quiz could be conducted. The quiz can be used to detect and narrow down student misconceptions in the context of the open switch.

The analysis of interview data does not ensure a sufficient, quantitative analysis. Hence, statements about the frequency of the misconceptions are imprecise. Therefore, the quiz could be used to confirm the proposed misconceptions and their specifications on a large number of students and to precisely determine the frequency of the observed misconceptions.

The second set of interviews has shown that the students' understanding changed differently for each student through the expanded studies in electrical engineering over the time of the lecture. It is conceivable to analyze the student understanding of some students over a longer period of time. Thus, having several interviews with the same students to gain a deeper insight into their process of understanding.

Further, the use of analogies should be investigated. This work has shown that some analogies cause more difficulties than help students in their understanding of electrical engineering. Different analogies should be investigated to answer which parts of the analogies are helpful and which parts are troublesome.

As the last point, teaching methods should be developed and used to prevent the observed misconceptions. The use of the open switch as a research context to investigate student misconceptions was beneficial in this work. Moreover, the second set of interviews has shown that the open switch questions and the debriefing helped some students in overcoming their misconceptions. Therefore, the use of the open switch in teaching courses might help in reducing students' misconceptions early on in their education. Further, the application of KVL to open circuits in tutorials may help students in their understanding of Kirchhoff's laws as well as their general understanding of voltage.

APPENDIX

A STUDENT INTERVIEWS

This chapter contains the E-Mails that asks the students to participate in the first and the second set of interviews, and the info sheet that was attached to the E-Mail, which asked the students to participate in the first interview. Further, Table 9 gives an overview of all students that participated in the interviews.

A.1 E-MAIL FIRST SET OF INTERVIEW - TRANSLATION

Dear students,

My name is Denise. Currently, I am writing my master's thesis in the Engineering Education Research Group at TUHH. I investigate the understanding of fundamentals in electrical engineering, and I need your help! I'd be happy if you are willing to let me interview you. The interviews will last 10-20 minutes, will take place over Zoom, and will NOT affect your grades in Electrical Engineering I. However, I will give you feedback after the interview. Therefore, you will benefit from it as well. It is not important to me if you answer right or wrong, but how you think about fundamental questions in electrical engineering! I have summarized all further information for you in the attachment.

Please register under this link *https://intranet.tuhh.de/termin/wiedenkstdu*. I will send you the Zoom access data by e-mail afterward.

I'd be happy if you support me!

Best regards Denise

A.2 E-MAIL FIRST SET OF INTERVIEWS - GERMAN ORIGINAL

Liebe Studierende,

mein Name ist Denise und derzeit schreibe ich meine Masterarbeit in der Fachdidaktik der TUHH. Ich möchte das Verständnis einiger elektrotechnischer Grundlagen untersuchen und brauche dafür eure Hilfe! Ich würde mich freuen, wenn ihr bereit wärt, euch von mir interviewen zu lassen. Die Interviews dauern 10-20 Minuten, finden über Zoom statt und haben KEINE Auswirkungen auf eure Noten in der Elektrotechnik I. Dennoch gebe ich euch danach ein Feedback, sodass auch ihr davon profitieren werdet. Mir ist es nicht wichtig, ob ihr richtig oder falsch antwortet, sondern wie ihr über einige fachliche Fragen der Elektrotechnik denkt! Alle weiteren Informationen habe ich für euch im Anhang zusammengefasst.

Meldet euch gerne unter diesem Link *https://intranet.tuhh.de/termin/wiedenkstdu* an. Die Zoom Zugangsdaten werde ich euch danach per Mail schicken.

Ich würde mich freuen, wenn ihr mich unterstützt!

Liebe Grüße Denise

A.3 E-MAIL ATTACHMENT FIRST SET OF INTERVIEWS - TRANSLATION

Who are you?

My name is Denise Duday. I am currently writing my master's thesis at the Engineering Education Research Group at TUHH.

Why are you doing this?

My master's thesis is about the fundamental understanding of electrical engineering. For that, I would like to conduct interviews to learn about students' understanding of electrical engineering.

Will this be recorded?

Yes, it will be recorded, but only with your consent. I do this so that I do not need somebody logging the interview, and I have a timeline of your notes. Since we are doing the interview via Zoom, you can just turn off the camera. If you want, you can get a copy of the transcript. So if I misunderstood something or if you have any comments, please feel free to include them. The data will be published anonymously and only in excerpts.

Does the interview affect my mark?

No, and if only a positive one. I just want to understand how you think about electrical engineering. Prof. Kuhl and also your tutors will not know about your performance in the interview. However, you may get a better grade in the exam because you understood the topic content better through this interview.

Why should I take part?

First of all, you get feedback on your understanding of electrical engineering. This is especially important because your entire degree will be built on these fundamentals. Further, the feedback will help you to prepare more effectively for the exam as you will know where to set the focus of your learning.

Second, after the interview, you can ask me questions about topics from the interview.

Third, hopefully, you will help improve teaching for the following students.

And lastly, you will help me with my master's thesis.

How long does this take?

The interview will be 10-20 minutes plus the time for your questions afterward.

Why did you choose me as a possible interviewee?

I am interested in talking to you because you are currently enrolled in the lecture *Electrical Engineering I*.

But I'm not good at electrical engineering...

That does not matter. It is not about right or wrong answers; it is about how you understand and think about electrical engineering. For the overall picture of my research, it is better to interview students of all levels anyway.

Where does the interview take place?

The interviews take place in an online Zoom-Room. I will send you the link to the room after you booked an appointment.

When does the interview take place?

You can book an appointment between 27.11.2020-18.12.2020 at *https://intranet.tuhh.de/termin/wiedenkstdu*.

What if I have further questions?

Feel free to send me an email (`Denise.Duday@tuhh.de`).

A.4 E-MAIL ATTACHMENT FIRST SET OF INTERVIEWS - GERMAN ORIGINAL

Wer bist du?

Ich heiße Denise Duday und schreibe momentan meine Masterarbeit in der Abteilung für Fachdidaktik der Ingenieurwissenschaften der TUHH.

Worum geht es?

In meiner Masterarbeit geht es um das Verständnis von elektrotechnischen Grundlagen. Dafür würde ich gerne Interviews durchführen.

Wird das Interview aufgenommen?

Ja, aber natürlich nur mit deiner Zustimmung. Und auch nur damit keiner Protokoll führen muss und man weiß, wann du was geschrieben/skizziert hast. Da wir das Interview über Zoom durchführen, kannst du einfach die Kamera ausschalten. Wenn du möchtest kannst du eine Kopie des Transkripts bekommen. Falls ich also etwas falsch verstanden habe oder du Anmerkungen dazu hast, können diese gerne noch mit aufgenommen werden.
Außerdem werden die Daten später nur anonymisiert und in Auszügen veröffentlicht.

Hat das Interview Einfluss auf meine Note?

Nein und wenn nur einen positiven. Ich möchte mir nur ein Bild zum Verständnis der Elektrotechnik machen. Herr Prof. Kuhl und auch deine Tutoren werden natürlich nichts von deiner Leistung im Interview erfahren. Tatsächlich kann es jedoch sein, dass du später eine bessere Note in der Klausur schreiben wirst, weil du Themeninhalte durch dieses Interview besser verstanden hast.

Wieso sollte ich mitmachen?

Erstens bekommst du so eine Einschätzung deines Verständnisses und deines Wissens in der Elektrotechnik. Dies ist besonders wichtig, weil auf diesen Grundlagen dein ganzes Studium aufbauen wird. Außerdem kannst du dich mit dieser Einschätzung deines Wissens effektiver auf die Klausur vorbereiten, weil du weißt, wo du Schwerpunkte beim Lernen setzen kannst.
Zweitens kannst du mir nach dem Interview noch Fragen zu Themen aus dem Interview stellen.
Drittens hilfst du hoffentlich die Lehre für nachfolgende Studenten zu verbessern.
Und zu guter Letzt hilfst du mir bei meiner Masterarbeit.

Wie lange dauert das Ganze?

Das Interview dauert etwa 10-20 Minuten plus die Zeit für deine Fragen danach.

Wieso willst du gerade mich interviewen?

Du bist ein interessanter Interviewpartner, weil du momentan die Vorlesung *Elektrotechnik I* hörst.

Aber ich bin nicht so gut in Elektrotechnik...

Das ist egal. Es geht nicht um richtige oder falsche Antworten, sondern darum, wie du Elektrotechnik verstehst und wie du denkst. Für das Gesamtbild meiner Untersuchung ist es ohnehin am besten, wenn ich Studierende aus allen möglichen Gruppen interviewe.

Wo wird das Interview stattfinden?

Das Interview wird über Zoom stattfinden. Die Zugangsdaten schicke ich dir, nachdem du dich für einen Termin eingetragen hast.

Wann wird das Interview stattfinden?

Such dir gerne zwischen dem 27.11.2020 - 18.12.2020 einen freien Termin über
https://intranet.tuhh.de/termin/wiedenkstdu aus.

Wie kann ich weitere Fragen stellen?

Schreib mir einfach eine E-Mail an `Denise.Duday@tuhh.de`.

A.5 E-MAIL SECOND SET OF INTERVIEWS - TRANSLATION

Hello [Student's Name],

After analyzing the interviews, I noticed that there are still a few details I would like to investigate further. I am aware that you have continued to study electrical engineering over the past few weeks. Still, I would like to have a second, short interview with you. This second interview should not take longer than 10-15 minutes, and you do not need to prepare for it.

From this Wednesday (27.01.) until 10.02. you are welcome to choose an appointment on any day between 09:00-16:00. Just write me a date and time that suits you.

I'd be happy if you would support me once again with my master thesis.

Best regards Denise

A.6 E-MAIL SECOND SET OF INTERVIEWS - GERMAN ORIGINAL

Hallo [Name des Studenten],

nachdem ich nun alle Interviews ausgewertet habe, ist mir aufgefallen, dass es noch ein paar Details gibt zu denen ich noch Fragen habe. Mir ist bewusst, dass du dich in den letzten Wochen weiter mit der Elektrotechnik beschäftigt hast, dennoch würde ich gerne noch ein zweites, kurzes Interview mit dir führen. Dieses zweite Interview sollte nicht länger als 10-15 Minuten dauern und du brauchst dich auch nicht darauf vorzubereiten.

Ab diesen Mittwoch (27.01.) bis zum 10.02. kannst du dir gerne zu jedem Tag zwischen 09:00-16:00 Uhr einen Termin aussuchen. Schreibe mir einfach einen Tag und Termin, der dir gut passt.

Ich würde mich freuen, wenn du mich noch einmal bei meiner Masterarbeit unterstützen würdest.

Viele Grüße Denise

A.7 OVERVIEW STUDENTS

Student	Subject	School Grade	Background Knowledge	Mentioned in	Second Interview
1	electrical engineering	2.7	No	Section 7.1, Section 7.3	No
2	mechatronics	2.0	Yes	Section 8.2	No
3	general engineering science	A[a]	No	Section 7.4	No
4	computer science	1.5	Yes	Not mentioned	No
5	electrical engineering	1.6	No	Not mentioned	No
6	computer science	1.0	No	Not mentioned	No
7	electrical engineering	1.2	Yes	Section 7.2	No
8	orientation semester	2.3	No	Section 7.3	No
9	general engineering	2.9	No	Section 7.5, Section 8.1	No
10	general engineering	1.7	No	Section 7.1, Section 8.3	Yes
11	general engineering	2.0	No	Section 7.3, Section 7.4	No
12	general engineering	3.1	No	Section 8.1	No
13	general engineering	1.9	No	Section 7.3	No
14	computer science	1.1	No	not mentioned	No
15	computer science	2.6	No	Section 7.3	No
16	general engineering	1.9	No	Section 7.1, Section 8.3	Yes
17	mechatronics	2.0	Yes	Section 7.2, Section 7.4	Yes
18	general engineering	1.0	No	Not mentioned	No
19	data science	1.5	No	Section 7.1, Section 7.2, Section 7.4, Section 7.5	Yes
20	electrical engineering	1.5	No	Section 7.3	Yes

Table 9: Overview of the students that participated in the first and the second set of interviews, their background, and sections in which the students are mentioned.

a This student completed their High School education abroad and graduated with an A, the best possible grade

B QUESTIONNAIRE

This part of the Appendix contains the quiz assignment for each circuit, the follow-up question, and the question charts.

The quiz assignment introduces the respective circuits and the lead question for each circuit, which asks about the voltage of the open switch. The quiz assignments are illustrated in Section B.1. Depending on the answer choice, different follow-up questions ensue to determine whether the student understood the concept of the open circuit correctly or to detect and narrow down possible misconceptions in the student's mental model. The follow-up questions for each circuit are listed in Section B.2. The question charts illustrate which answer option indicates which misconception. The question charts are illustrated in Section B.3.

B.1 QUIZ ASSIGNMENTS

Figure 13, Figure 14, Figure 15 and Figure 16 illustrate the respective circuits, necessary information about the circuits and the lead question 1, 2, 3, 4a and 4b for each circuit. The circuit 4 has two lead questions, question 4a and question 4b, as it has two open switches.

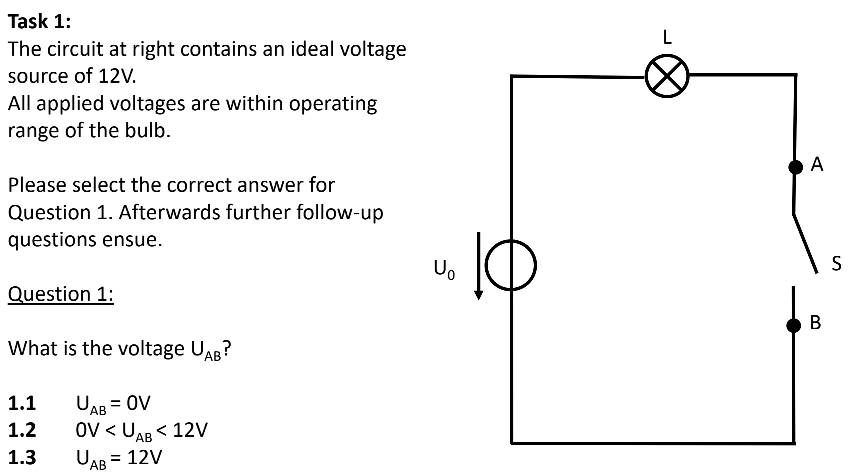


Figure 13: Quiz Assignment of Circuit 1.

Task 2:
The circuit at right contains an ideal voltage source of 12V.
The bulbs are all identical. All applied voltages are within operating range of the bulbs.

Please select the correct answer for Question 2. Afterwards further follow-up questions ensue.

Question 2:

What is the voltage U_{DF}?

2.1 $U_{DF} = 0V$
2.2 $0V < U_{DF} < 12V$
2.3 $U_{DF} = 12V$

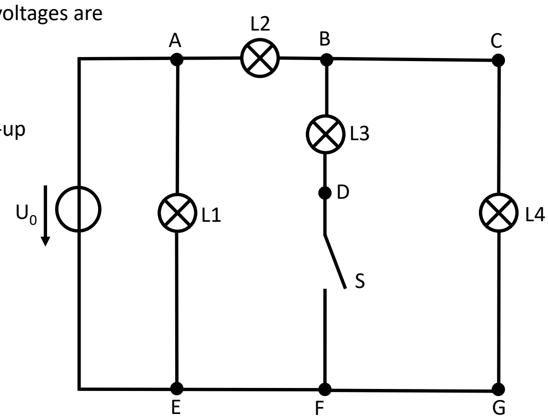


Figure 14: Quiz Assignment of Circuit 2.

Task 3:
The circuit at right contains ideal voltage sources of 12V.
The two bulbs are identical. All applied voltages are within operating range of the bulbs.

Please select the correct answer for Question 3. Afterwards further follow-up questions ensue.

Question 3:

What is the voltage U_{AB}?

3.1 $U_{AB} = 0V$
3.2 $0V < U_{AB} < 12V$
3.3 $U_{AB} = 12V$
3.4 $12V < U_{AB} < 24V$
3.5 $U_{AB} = 24V$

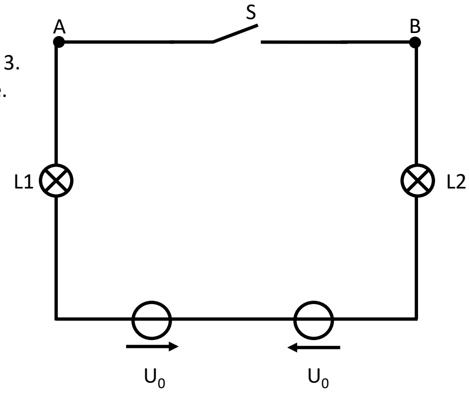
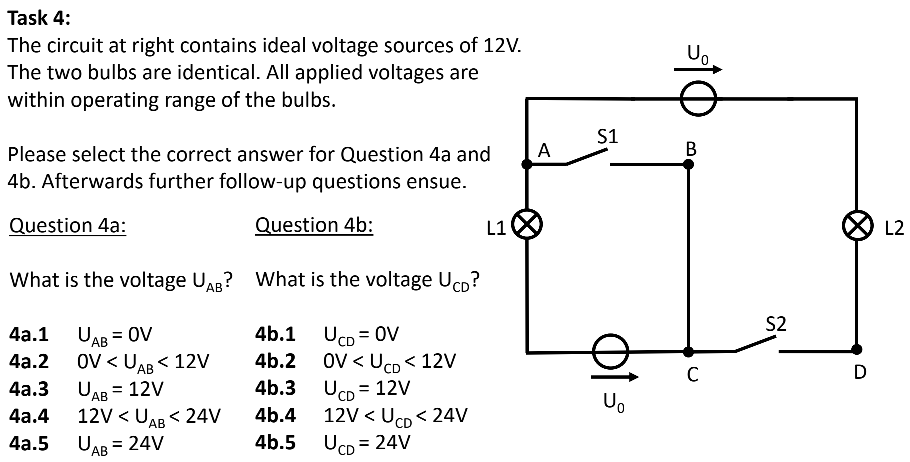


Figure 15: Quiz Assignment of Circuit 3.


Task 4:
The circuit at right contains ideal voltage sources of 12V. The two bulbs are identical. All applied voltages are within operating range of the bulbs.

Please select the correct answer for Question 4a and 4b. Afterwards further follow-up questions ensue.

Question 4a:		Question 4b:	
What is the voltage U_{AB}?		What is the voltage U_{CD}?	
4a.1	U_{AB} = 0V	**4b.1**	U_{CD} = 0V
4a.2	0V < U_{AB} < 12V	**4b.2**	0V < U_{CD} < 12V
4a.3	U_{AB} = 12V	**4b.3**	U_{CD} = 12V
4a.4	12V < U_{AB} < 24V	**4b.4**	12V < U_{CD} < 24V
4a.5	U_{AB} = 24V	**4b.5**	U_{CD} = 24V

Figure 16: Quiz Assignment of Circuit 4.

B.2 FOLLOW-UP QUESTIONS OF THE QUIZ

Depending on the student's answer choice in the lead questions for each circuit, different follow-up questions ensue. The lead questions, as well as the follow-up questions, are mostly MC SR questions. The order of the follow-up questions is listed in Section B.3. In this section, all follow-up questions for each circuit are listed, respectively.

The numbering of the follow-up questions is based on the previous answer choice. For example, for lead question 1, the follow-up question to the answer option 1.1 of question 1 is indicated as question 1.1. The answer options of question 1.1 are numbered by adding consecutive numbers, for example, 1.1.1 and 1.1.2. The follow-up questions of the lead questions 2, 3, 4a, and 4b are numbered accordingly.

Although not specifically indicated, the answer option "Other?" should lead to a text field in which the student can explain their thoughts. After an "Other" no further follow-up questions ensue.

B.2.1 *Follow-Up Questions Circuit 1*

Question 1: What is the voltage U_{AB}?

1.1 $U_{AB} = 0V$.

1.2 $0V < U_{AB} < 12V$.

1.3 $U_{AB} = 12V$.

Question 1.1: Why is the voltage $U_{AB} = 0V$?

1.1.1 According to Ohm's law, the voltage $U_{AB} = 0V$.

1.1.2 No voltage flows in the branch with the open switch, therefore $U_{AB} = 0V$.

1.1.3 No current flows in the branch with the open switch, therefore the voltage $U_{AB} = 0V$.

1.1.4 Other?

Question 1.1.1: What does the application of Ohm's law yield that the voltage across the open switch $U_{AB} = 0V$?

1.1.1.1 The current in the branch with the open switch is zero. Hence, when applying Ohm's law, the voltage is zero as well.

1.1.1.2 The resistance of the open switch is zero. Hence, when applying Ohm's law, the voltage is zero as well.

1.1.1.3 Both the current in the branch of the open switch and the resistance of the open switch are zero. Hence, when applying Ohm's law, the voltage is zero as well.

1.1.1.4 Other?

Question 1.1.2a: No voltage flows in the branch with the open switch, therefore $U_{AB} = 0V$. Which statement about the voltage is correct?

1.1.2a.1 The voltage flows out of the switch.

1.1.2a.2 The voltage does not start flowing.

1.1.2a.3 Other?

Question 1.1.2b: Which statements about Kirchhoff's laws are correct?

1.1.2b.1 KVL can be applied to open and closed loops.

1.1.2b.2 KVL can only be applied to closed loops.

Question 1.1.3: Why is the voltage $U_{AB} = 0V$ when no current flows in the branch with the open switch?

1.1.3.1 Because voltage and current always appear together. Hence, if no current flows between the two points, no voltage drops there either.

1.1.3.2 Because current causes voltage. Hence, if no current flows between the two points, no voltage drops.

1.1.3.3 Because voltage is a property of current. Hence, if no current flows between the two points, no voltage drops.

1.1.3.4 Other?

Question 1.1.3.2: What does current causes voltage?

1.1.3.2.1 Moving charge carriers cause the voltage.

1.1.3.2.2 Moving charge carriers cause the electrical potential.

1.1.3.2.3 Other?

Question 1.1.3.3: What is voltage a property of current?

1.1.3.3.1 Voltage is the energy of the charge carriers.

1.1.3.3.2 Voltage is the velocity of the charge carriers.

1.1.3.3.3 Voltage is the force on the charge carriers.

1.1.3.3.4 Other?

Question 1.2: Please explain why the voltage is $0V < U_{AB} < 12V$?

Question 1.3: Why is the voltage $U_{AB} = 12V$?

1.3.1 The voltage is the same everywhere in the circuit. Hence, the voltage $U_{AB} = 12V$ as well.

1.3.2 The potential at point $\Phi_A = 12V$.

1.3.3 According to KVL $U_{AB} = 12V$.

1.3.4 Other?

Question 1.3.3: Please explain how according to KVL the voltage is $U_{AB} = 12V$.

B.2.2 *Follow-Up Questions Circuit 2*

Question 2: What is the voltage U_{DF}?

2.1 $U_{DF} = 0V$.

2.2 $0V < U_{DF} < 12V$.

2.3 $U_{DF} = 12V$.

Question 2.1: Why is the voltage $U_{DF} = 0V$?

2.1.1 According to Ohm's law, the voltage $U_{DF} = 0V$.

2.1.2 No voltage flows in the branch with the open switch, therefore $U_{DF} = 0V$.

2.1.3 No current flows in the branch with the open switch, therefore the voltage $U_{DF} = 0V$.

2.1.4 Other?

Question 2.1.1: What does the application of Ohm's law yield that the voltage across the open switch $U_{DF} = 0V$?

2.1.1.1 The current in the branch with the open switch is zero. Hence, when applying Ohm's law, the voltage is zero as well.

2.1.1.2 The resistance of the open switch is zero. Hence, when applying Ohm's law, the voltage is zero as well.

2.1.1.3 Both the current in the branch of the open switch and the resistance of the open switch are zero. Hence, when applying Ohm's law, the voltage is zero as well.

2.1.1.4 Other?

Question 2.1.2a: No voltage flows in the branch with the open switch, therefore $U_{DF} = 0V$. Which statement about the voltage is correct?

2.1.2a.1 The voltage flows out of the switch.

2.1.2a.2 The voltage does not start flowing.

2.1.2a.3 The voltage does not flow into the BF-branch because the switch is open.

2.1.2a.4 Other?

Question 2.1.2b: Which statements about Kirchhoff's laws are correct?

2.1.2b.1 KVL can be applied to open and closed loops.

2.1.2b.2 KVL can only be applied to closed loops.

2.1.2b.3 When the switch is closed, the voltage divides at the branch with the switch according to KCL.

Question 2.1.3: Why is the voltage $U_{DF} = 0V$ when no current flows in the branch with the open switch?

2.1.3.1 Because voltage and current always appear together. Hence, if no current flows between the two points, no voltage drops there either.

2.1.3.2 Because current causes voltage. Hence, if no current flows between the two points, no voltage drops.

2.1.3.3 Because voltage is a property of current. Hence, if no current flows between the two points, no voltage drops.

2.1.3.4 Other?

Question 2.1.3.2: What does current causes voltage?

2.1.3.2.1 Moving charge carriers cause the voltage.

2.1.3.2.2 Moving charge carriers cause the electrical potential.

2.1.3.2.3 Other?

Question 1.1.3.3: What is voltage a property of current?

2.1.3.3.1 Voltage is the energy of the charge carriers.

2.1.3.3.2 Voltage is the velocity of the charge carriers.

2.1.3.3.3 Voltage is the force on the charge carriers.

2.1.3.3.4 Other?

Question 2.2: What is the voltage U_{DF}?

2.2.1 $U_{DF} = U_{AE}$.

2.2.2 $U_{DF} = U_{BD}$.

2.2.3 $U_{DF} = U_{CG}$.

2.2.4 Other?

Question 2.2.1: Please explain why the voltage is $U_{DF} = U_{AE}$.

Question 2.2.2: Please explain why the voltage is $U_{DF} = U_{BD}$.

Question 2.2.3: Please explain why the voltage is $U_{DF} = U_{CG}$.

Question 2.3: Why is the voltage $U_{DF} = 12V$?

2.3.1 The voltage is the same everywhere in the circuit. Hence, the voltage $U_{DF} = 12V$ as well.

2.3.2 The potential at point $\Phi_D = 12V$.

2.3.3 Other?

B.2.3 *Follow-Up Questions Circuit 3*

Question 3: What is the voltage U_{AB}?

3.1 $U_{AB} = 0V$.

3.2 $0V < U_{AB} < 12V$.

3.3 $U_{AB} = 12V$.

3.4 $12V < U_{AB} < 24V$.

3.5 $U_{AB} = 24V$.

Question 3.1: Why is the voltage $U_{AB} = 0V$?

3.1.1 According to Ohm's law, the voltage $U_{AB} = 0V$.

3.1.2 No voltage flows in the branch with the open switch, therefore $U_{AB} = 0V$.

3.1.3 No current flows in the branch with the open switch, therefore the voltage $U_{AB} = 0V$.

3.1.4 According to KVL $U_{AB} = 0V$.

3.1.5 Other?

Question 3.1.1: What does the application of Ohm's law yield that the voltage across the open switch $U_{AB} = 0V$?

3.1.1.1 The current in the branch with the open switch is zero. Hence, when applying Ohm's law, the voltage is zero as well.

3.1.1.2 The resistance of the open switch is zero. Hence, when applying Ohm's law, the voltage is zero as well.

3.1.1.3 Both the current in the branch of the open switch and the resistance of the open switch are zero. Hence, when applying Ohm's law, the voltage is zero as well.

3.1.1.4 Other?

Question 3.1.2a: No voltage flows in the branch with the open switch, therefore $U_{AB} = 0V$. Which statement about the voltage is correct?

3.1.2a.1 The voltage flows out of the switch.

3.1.2a.2 The voltage does not start flowing.

3.1.2a.3 Other?

Question 3.1.2b: Which statements about Kirchhoff's laws are correct?

3.1.2b.1 KVL can be applied to open and closed loops.

3.1.2b.2 KVL can only be applied to closed loops.

Question 3.1.3: Why is the voltage $U_{AB} = 0V$ when no current flows in the branch with the open switch?

3.1.3.1 Because voltage and current always appear together. Hence, if no current flows between the two points, no voltage drops there either.

3.1.3.2 Because current causes voltage. Hence, if no current flows between the two points, no voltage drops.

3.1.3.3 Because voltage is a property of current. Hence, if no current flows between the two points, no voltage drops.

3.1.3.4 Other?

Question 3.1.3.2: What does current causes voltage?

3.1.3.2.1 Moving charge carriers cause the voltage.

3.1.3.2.2 Moving charge carriers cause the electrical potential.

3.1.3.2.3 Other?

Question 3.1.3.3: What is voltage a property of current?

3.1.3.3.1 Voltage is the energy of the charge carriers.

3.1.3.3.2 Voltage is the velocity of the charge carriers.

3.1.3.3.3 Voltage is the force on the charge carriers.

3.1.3.3.4 Other?

Question 3.1.4: Please explain how according to KVL the voltage is $U_{AB} = 0V$.

Question 3.2: Please explain why the voltage is $0V < U_{AB} < 12V$?

Question 3.3: Why is the voltage $U_{AB} = 12V$?

3.3.1 The voltage is the same everywhere in the circuit. Hence, the voltage $U_{AB} = 12V$ as well.

3.3.2 The potential at point $\Phi_A = 12V$.

3.3.3 Other?

Question 3.4: Please explain why the voltage is $12V < U_{AB} < 24V$?

Question 3.5: Why is the voltage $U_{AB} = 24V$?

3.5.1 The voltage is the same everywhere in the circuit. Hence, the voltage $U_{AB} = 24V$ as well.

3.5.2 The potential at point $\Phi_A = 24V$.

3.5.3 Other?

B.2.4 *Follow-Up Questions Circuit 4*

Question 4a: What is the voltage U_{AB}?

4a.1 $U_{AB} = 0V$.

4a.2 $0V < U_{AB} < 12V$.

4a.3 $U_{AB} = 12V$.

4a.4 $12V < U_{AB} < 24V$.

4a.5 $U_{AB} = 24V$.

Question 4a.1: Why is the voltage $U_{AB} = 0V$?

4a.1.1 According to Ohm's law, the voltage $U_{AB} = 0V$.

4a.1.2 No voltage flows in the branch with the open switch, therefore $U_{AB} = 0V$.

4a.1.3 No current flows in the branch with the open switch, therefore the voltage $U_{AB} = 0V$.

4a.1.4 Other?

Question 4a.1.1: What does the application of Ohm's law yield that the voltage across the open switch $U_{AB} = 0V$?

4a.1.1.1 The current in the branch with the open switch is zero. Hence, when applying Ohm's law, the voltage is zero as well.

4a.1.1.2 The resistance of the open switch is zero. Hence, when applying Ohm's law, the voltage is zero as well.

4a.1.1.3 Both the current in the branch of the open switch and the resistance of the open switch are zero. Hence, when applying Ohm's law, the voltage is zero as well.

4a.1.1.4 Other?

Question 4a.1.2a: No voltage flows in the branch with the open switch, therefore $U_{AB} = 0V$. Which statement about the voltage is correct?

4a.1.2a.1 The voltage flows out of the switch.

4a.1.2a.2 The voltage does not start flowing.

4a.1.2a.3 If the switch S1 is open and the switch S2 is closed, the voltage does not flow into the branch with the open switch S1 because the switch S1 is open.

4a.1.2a.4 Other?

Question 4a.1.2b: Which statements about Kirchhoff's laws are correct?

4a.1.2b.1 KVL can be applied to open and closed loops.

4a.1.2b.2 KVL can only be applied to closed loops.

4a.1.2b.3 When the switches are closed, the voltage divides at A and C according to KCL.

Question 4a.1.3: Why is the voltage $U_{AB} = 0V$ when no current flows in the branch with the open switch?

4a.1.3.1 Because voltage and current always appear together. Hence, if no current flows between the two points, no voltage drops there either.

4a.1.3.2 Because current causes voltage. Hence, if no current flows between the two points, no voltage drops.

4a.1.3.3 Because voltage is a property of current. Hence, if no current flows between the two points, no voltage drops.

4a.1.3.4 Other?

Question 4a.1.3.2: What does current causes voltage?

4a.1.3.2.1 Moving charge carriers cause the voltage.

4a.1.3.2.2 Moving charge carriers cause the electrical potential.

4a.1.3.2.3 Other?

Question 4a.1.3.3: What is voltage a property of current?

4a.1.3.3.1 Voltage is the energy of the charge carriers.

4a.1.3.3.2 Voltage is the velocity of the charge carriers.

4a.1.3.3.3 Voltage is the force on the charge carriers.

4a.1.3.3.4 Other?

Question 4a.2: Please explain why the voltage is $0\text{V} < U_{AB} < 12\text{V}$?

Question 4a.3: Why is the voltage $U_{AB} = 12\text{V}$?

4a.3.1 The voltage is the same everywhere in the circuit. Hence, the voltage $U_{AB} = 12\text{V}$ as well.

4a.3.2 The potential at point $\Phi_A = 12\text{V}$.

4a.3.3 According to KVL $U_{AB} = 12\text{V}$.

4a.3.4 Other?

Question 4a.3.3: Please explain how according to KVL the voltage is $U_{AB} = 12\text{V}$.

Question 4a.4: Please explain why the voltage is $12\text{V} < U_{AB} < 24\text{V}$?

Question 4a.5: Why is the voltage $U_{AB} = 24\text{V}$?

4a.5.1 The voltage is the same everywhere in the circuit. Hence, the voltage $U_{AB} = 24\text{V}$ as well.

4a.5.2 The potential at point $\Phi_A = 24\text{V}$.

4a.5.3 Other?

Question 4b: What is the voltage U_{CD}?

4b.1 $U_{CD} = 0\text{V}$.

4b.2 $0\text{V} < U_{CD} < 12\text{V}$.

4b.3 $U_{CD} = 12\text{V}$.

4b.4 $12\text{V} < U_{CD} < 24\text{V}$.

4b.5 $U_{CD} = 24\text{V}$.

Question 4b.1: Why is the voltage $U_{CD} = 0\text{V}$?

4b.1.1 According to Ohm's law, the voltage $U_{CD} = 0\text{V}$.

4b.1.2 No voltage flows in the branch with the open switch, therefore $U_{CD} = 0\text{V}$.

4b.1.3 No current flows in the branch with the open switch, therefore the voltage $U_{CD} = 0\text{V}$.

4b.1.4 According to KVL $U_{CD} = 0\text{V}$.

4b.1.5 Other?

Question 4b.1.1: What does the application of Ohm's law yield that the voltage across the open switch $U_{CD} = 0\text{V}$?

4b.1.1.1 The current in the branch with the open switch is zero. Hence, when applying Ohm's law, the voltage is zero as well.

4b.1.1.2 The resistance of the open switch is zero. Hence, when applying Ohm's law, the voltage is zero as well.

4b.1.1.3 Both the current in the branch of the open switch and the resistance of the open switch are zero. Hence, when applying Ohm's law, the voltage is zero as well.

4b.1.1.4 Other?

Question 4b.1.2a: No voltage flows in the branch with the open switch, therefore $U_{CD} = 0V$. Which statement about the voltage is correct?

4b.1.2a.1 The voltage flows out of the switch.

4b.1.2a.2 The voltage does not start flowing.

4b.1.2a.3 If the switch S1 is open and the switch S2 is closed, the voltage does not flow into the branch with the open switch S2 because the switch S2 is open.

4b.1.2a.4 Other?

Question 4b.1.2b: Which statements about Kirchhoff's laws are correct?

4b.1.2b.1 KVL can be applied to open and closed loops.

4b.1.2b.2 KVL can only be applied to closed loops.

4b.1.2b.3 When the switches are closed, the voltage divides at A and C according to KCL.

Question 4b.1.3: Why is the voltage $U_{CD} = 0V$ when no current flows in the branch with the open switch?

4b.1.3.1 Because voltage and current always appear together. Hence, if no current flows between the two points, no voltage drops there either.

4b.1.3.2 Because current causes voltage. Hence, if no current flows between the two points, no voltage drops.

4b.1.3.3 Because voltage is a property of current. Hence, if no current flows between the two points, no voltage drops.

4b.1.3.4 Other?

Question 4b.1.3.2: What does current causes voltage?

4b.1.3.2.1 Moving charge carriers cause the voltage.

4b.1.3.2.2 Moving charge carriers cause the electrical potential.

4b.1.3.2.3 Other?

Question 4b.1.3.3: What is voltage a property of current?

4b.1.3.3.1 Voltage is the energy of the charge carriers.

4b.1.3.3.2 Voltage is the velocity of the charge carriers.

4b.1.3.3.3 Voltage is the force on the charge carriers.

4b.1.3.3.4 Other?

Question 4b.1.4: Please explain how according to KVL the voltage is $U_{CD} = 0V$.

Question 4b.2: Please explain why the voltage is $0V < U_{AB} < 12V$?

Question 4b.3: Why is the voltage $U_{CD} = 12V$?

4b.3.1 The voltage is the same everywhere in the circuit. Hence, the voltage $U_{CD} = 12V$ as well.

4b.3.2 The potential at point $\Phi_C = 12V$.

4b.3.3 Other?

Question 4b.4: Please explain why the voltage is $12V < U_{AB} < 24V$?

Question 4b.5: Why is the voltage $U_{CD} = 24V$?

4b.5.1 The voltage is the same everywhere in the circuit. Hence, the voltage $U_{CD} = 24V$ as well.

4b.5.2 The potential at point $\Phi_C = 24V$.

4b.5.3 Other?

B.3 QUESTION CHARTS

Figure 17, Figure 18, Figure 19, Figure 20 and Figure 21 give an overview of the respective lead question and their follow-up questions. The purple number depicts the latest answer option. Marked with a red frame are the misconceptions that are likely held by the student, based on the student's previous answers. The blue framed boxes further specify some of those misconceptions. The green frame indicates a correct answer option. However, the green frame does not necessarily mean that the student correctly understood the concept open switch. Further, brown frames are used to indicate that a question that asks the students to further explain their understanding is recommended. However, explain-questions are not specifically listed in the follow-up questions.

For lead question 1, the misconception of understanding voltage as a substance is identified by answer 1.1.2 in question 1.1. If the student chose answer 1.1.2 in question 1.1, the questions 1.1.2a and

1.1.2b both ensue in the student's questionnaire. Regardless of the answer in 1.1.2a, question 1.1.2b is asked afterward. Both questions, question 1.1.2a, and question 1.1.2b are used to further specify the misconception of voltage being a substance that moves through the circuit. Moreover, question 1.1.2b can identify the misconception of only applying KVL to closed circuits. The same applies to the lead questions 2, 3, 4a, 4b, respectively.

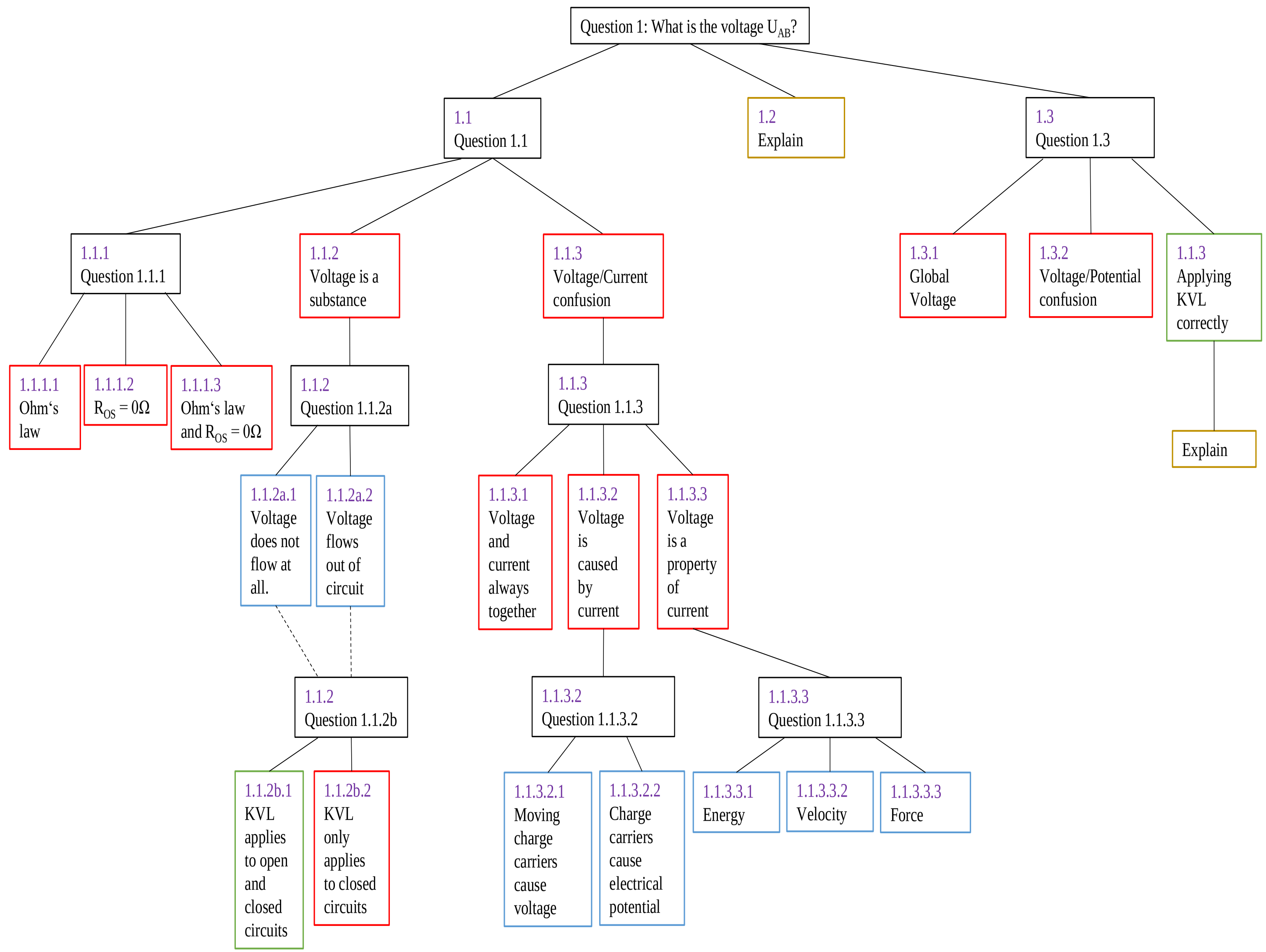


Figure 17: Question Chart of Question 1. Purple numbers indicate the latest answer option. Red frames indicate possible misconceptions of the student. Blue frames indicate a specialization of the misconception. Brown frames indicate that an "Explain" text field should ensue. Green frames indicate correct answers.

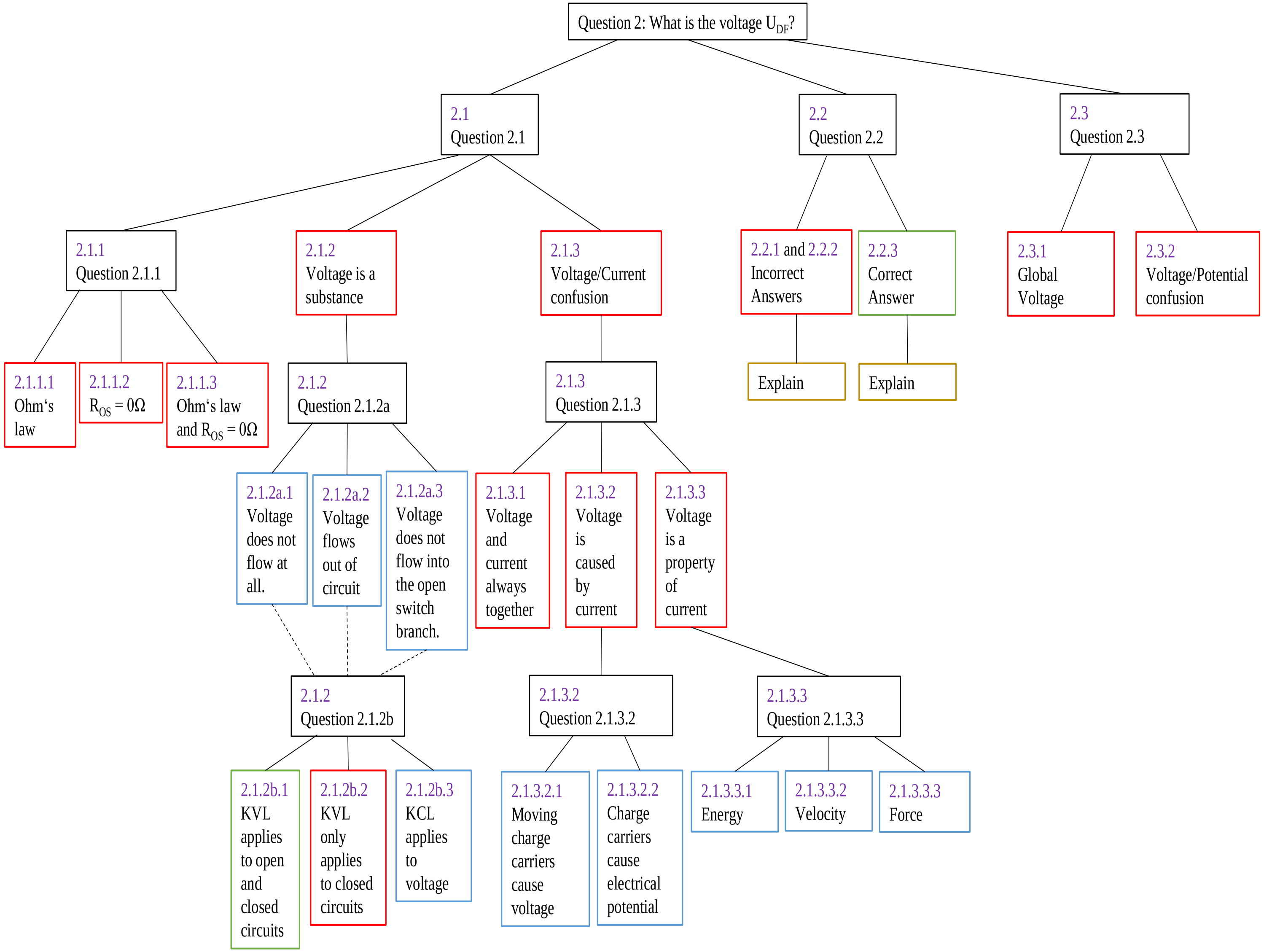


Figure 18: Question Chart of Question 2. Purple numbers indicate the latest answer option. Red frames indicate possible misconceptions of the student. Blue frames indicate a specialization of the misconception. Brown frames indicate that an "Explain" text field should ensue. Green frames indicate correct answers.

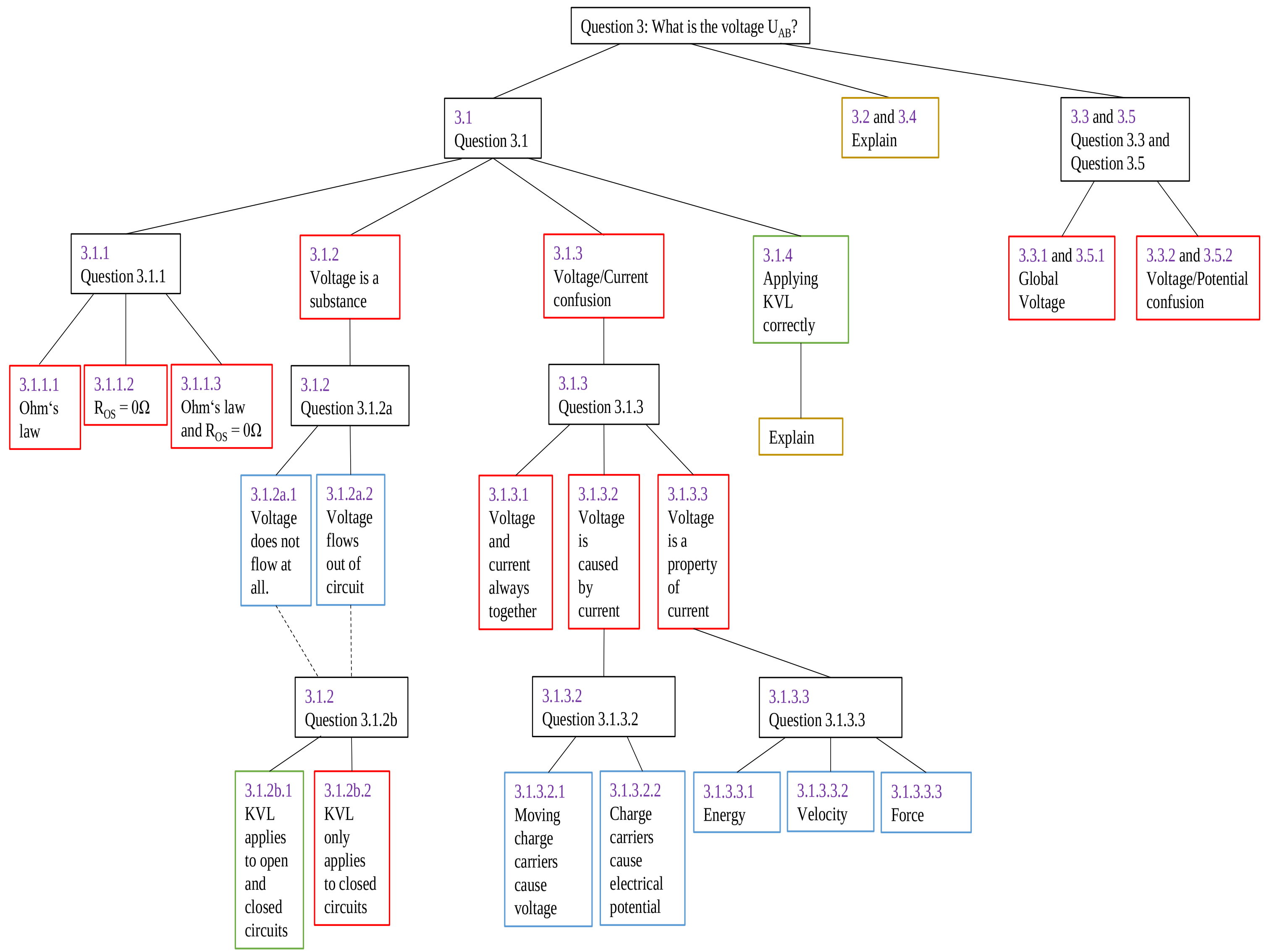


Figure 19: Question Chart of Question 3. Purple numbers indicate the latest answer option. Red frames indicate possible misconceptions of the student. Blue frames indicate a specialization of the misconception. Brown frames indicate that an "Explain" text field should ensue. Green frames indicate correct answers.

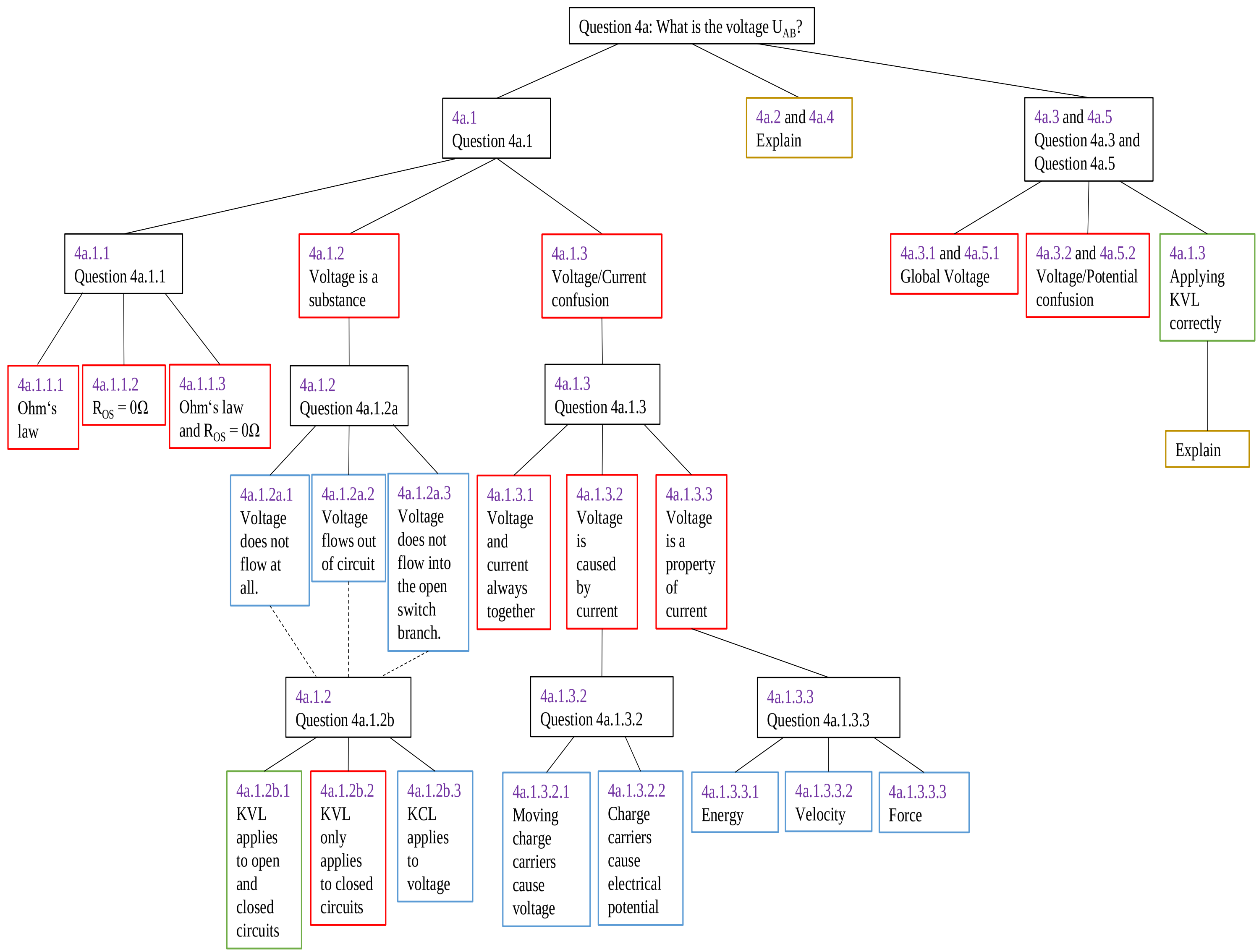


Figure 20: Question Chart of Question 4a. Purple numbers indicate the latest answer option. Red frames indicate possible misconceptions of the student. Blue frames indicate a specialization of the misconception. Brown frames indicate that an "Explain" text field should ensue. Green frames indicate correct answers.

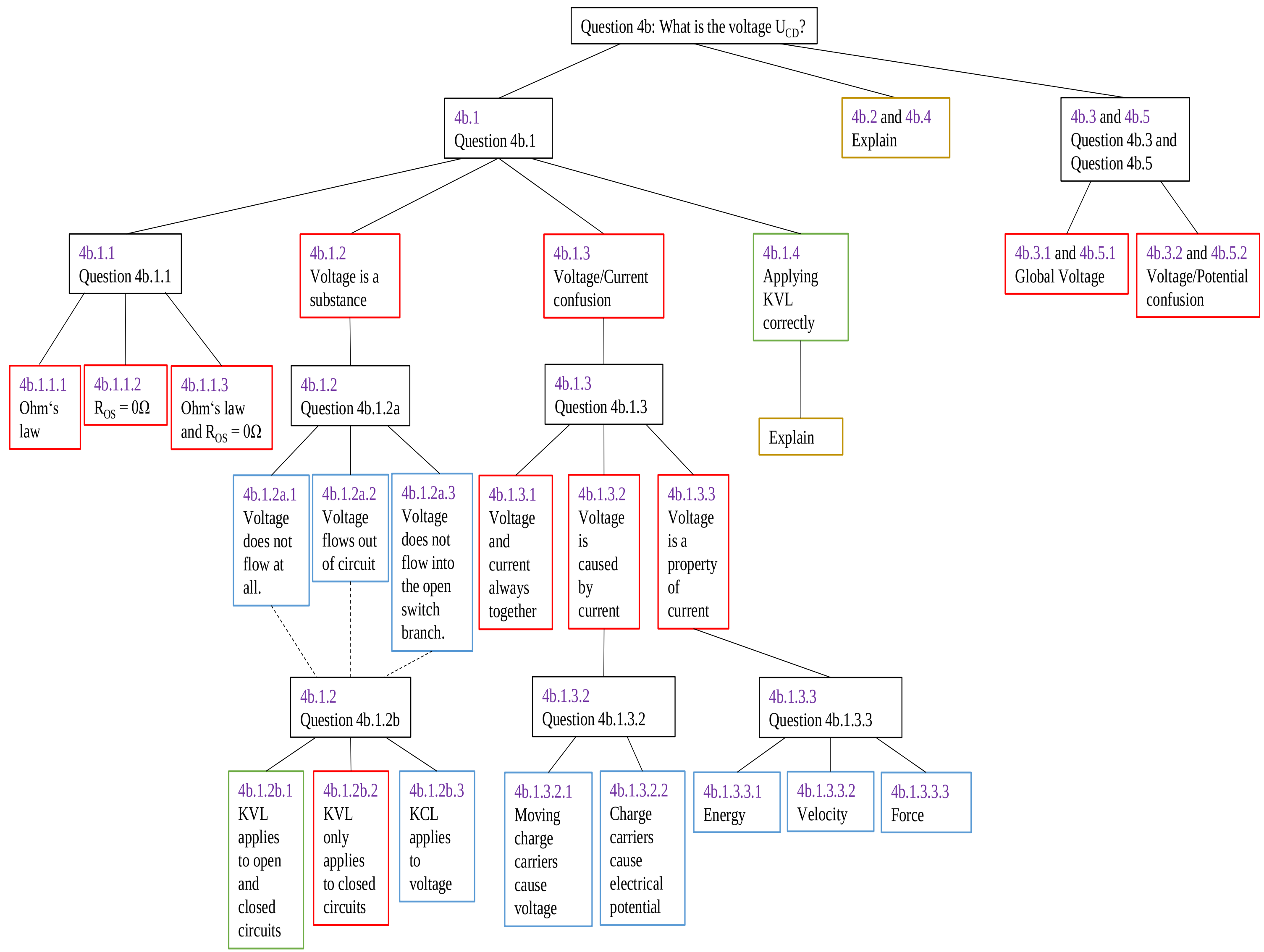


Figure 21: Question Chart of Question 4b. Purple numbers indicate the latest answer option. Red frames indicate possible misconceptions of the student. Blue frames indicate a specialization of the misconception. Brown frames indicate that an "Explain" text field should ensue. Green frames indicate correct answers.

BIBLIOGRAPHY

Maura Borrego, Elliot P. Douglas, and Catherine T. Amelink. Quantitative, Qualitative, and Mixed Research Methods in Engineering Education. *Journal of Engineering Education*, 98(1):53–66, January 2009. ISSN 10694730. doi: 10.1002/j.2168-9830.2009.tb01005.x. URL http://doi.wiley.com/10.1002/j.2168-9830.2009.tb01005.x.

R. Cohen, B. Eylon, and U. Ganiel. Potential difference and current in simple electric circuits: A study of students' concepts. *American Journal of Physics*, 51(5):407–412, 1983. doi: http://dx.doi.org/10.1119/1.13226. URL http://scitation.aip.org/content/aapt/journal/ajp/51/5/10.1119/1.13226.

Paula Vetter Engelhardt. *Examining students' understanding of electrical circuits through multiple-choice testing and interviews*. PhD thesis, North Carolina State University, December 1997.

Tatiana Goris. *Analysis of misconceptions of engineering technology students about electricity and circuits. A mixed methods study.* PhD thesis, Purdue University, 2012.

David Hammer. More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research. *American Journal of Physics*, 64(10):1316–1325, 1996. ISSN 00029505. doi: 10.1119/1.18376. URL http://link.aip.org/link/?AJP/64/1316/1&Agg=doi.

Noor Hamizah Hussain, Liza Abdul Latiff, and Nazli Yahaya. Alternative conception about open and short circuit concepts. *Procedia - Social and Behavioral Sciences*, 56:466–473, October 2012. ISSN 18770428. doi: 10.1016/j.sbspro.2012.09.678. URL http://linkinghub.elsevier.com/retrieve/pii/S1877042812041407.

Anker Helms Jørgensen. Thinking-aloud in user interface design: a methodpromoting cognitive ergonomics. 2007.

Harry V. Kincaid and Margaret Bright. The Tandem Interview:A Trial of the Two-InterviewerTeam, 1957.

Eric Mazur. *Peer instruction: A user's manual*. Prentice Hall, Upper Saddle River, N.J., 1997. ISBN 978-0-13-565441-5.

Lillian C. McDermott and Peter S. Shaffer. Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding. *American Journal* *of Physics*, 60(11):994–1003, November 1992. ISSN 0002-9505, 1943-2909. doi: 10.1119/1.17003. URL http://aapt.scitation.org/doi/10.1119/1.17003.

Lillian C. McDermott and Emily H. van Zee. Identifying and addressing student difficulties with electric circuits. In *Aspects of Understanding Electricity: Proceedings of the International Workshop*, pages 39 – 48. Kiel, 1985.

Jan H. F. Meyer and Ray Land. Threshold concepts and troublesome knowledge: linkages to ways of thinking and practising within the disciplines. In C. Rust, editor, *Improving Student Learning - Theory and Practice Ten Years On*, pages 412–424. OCSLD, Oxford, 2003. URL https://www.dkit.ie/ga/system/files/Threshold_Concepts__and_Troublesome_Knowledge_by_Professor_Ray_Land.pdf.

M. Cristina Periago and Xavier Bohigas. A study of second-year engineering students' alternative conceptions about electric potential, current intensity and Ohm's law. *European Journal of Engineering Education*, 30(1):71–80, March 2005a. ISSN 0304-3797, 1469-5898. doi: 10.1080/03043790410001711225. URL http://www.tandfonline.com/doi/abs/10.1080/03043790410001711225.

María Cristina Periago and Xavier Bohigas. The persistence of prior concepts about electric potential, current intensity and Ohm's law in students of engineering. *Revista Electrónica de Investigación Educativa*, 7(2):2, 2005b.

George J. Posner, Kenneth A. Strike, Peter W. Hewson, and William A. Gertzog. Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, 66(2):211–227, 1982. URL http://onlinelibrary.wiley.com/doi/10.1002/sce.3730660207/full.

Saed Ahmad Sabah. *Developing a two-tiered instrument with confidence levels for assessing students' conceptions of Direct Current circuits*. PhD thesis, 2007.

Steven E Schwarz and William G Oldham. *Electrical engineering: An introduction*. Oxford University Press, New York, 1993. ISBN 978-0-19-510587-2 978-0-19-510585-8.

Brian J. Skromme and Dan Robinson. Addressing barriers to learning in linear circuit analysis. In *2015 ASEE Annual Conference and Exposition*, Seattle, Washington, June 2015. URL https://peer.asee.org/23497.

Chris R. Smaill, Gerard B. Rowe, Elizabeth Godfrey, and Rod O. Paton. An investigation into the understanding and skills of first-year electrical engineering students. *IEEE Transactions on Education*, 55(1):29–35, February 2012. ISSN 0018-9359, 1557-9638. doi: 10.1109/TE.2011.2114663. URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5722055.

David P. Smith and Paul van Kampen. Teaching electric circuits with multiple batteries: A qualitative approach. *Physical Review Special Topics - Physics Education Research*, 7(2), November 2011. ISSN 1554-9178. doi: 10.1103/PhysRevSTPER.7.020115. URL http://link.aps.org/doi/10.1103/PhysRevSTPER.7.020115.

Kenneth A. Strike and George J. Posner. A revisionist theory of conceptual change. In Richard A. Duschl and Richard J. Hamilton, editors, *Philosophy of science, cognitive science, and educational theory and practice*. SUNY Press, Albany, NY, 1992.

U. Tietze, Ch Schenk, and E. Gamm. *Electronic circuits: handbook for design and application*. Springer-Verlag Berlin Heidelberg, New York, 2nd ed edition, 2008. ISBN 978-3-540-00429-5.

Dion Timmermann. *Engineering Students' Understanding of Basic Electric Circuit Concepts and the Effect of Qualitative Worksheets*. doctoralThesis, Technische Universität Hamburg, Hamburg, Germany, 2020. URL https://doi.org/10.15480/882.2958. Series: Hamburg Advances in Science and Engineering Education Research DOI: 10.15480/882.2958.

Dion Timmermann and Christian Kautz. Multiple-choice questions that test conceptual understanding: A proposal for qualitative two-tier exam questions. In *Proceedings of the 122nd ASEE Annual Conference & Exposition*, Seattle, WA, USA, 2015.

TUHH. Modulhandbuch B.Sc. Elektrotechnik, April 2020. URL https://studienplaene.tuhh.de/po/E/mhb_ETBS_kh_w20_von_20200430_v_0_de.pdf.

C. von Rhöneck. Student conceptions of the electric circuit before physics instruction. In *Paper presented at the International Workshop on Problems Concerning Students' Representation of Physics and Chemistry Knowledge*, pages 194–212, Pädagogische Hochschule, Ludwigsburg, 1982.

C von Rhöneck and B Volker. Semantic structures describing the electric circuit before and after instruction. In R. Duit, W. Jung, and C. von Rhöneck, editors, *Aspects of Understanding Electricity. Proceedings of an International Workshop in Ludwigsburg 1984*, 1985.

Christoph von Rhöneck. Energetic aspects of students' conceptions before and after first formal instruction. In *Four decades of research in science education - From curriculum development to quality improvement*, pages 69–84. Waxmann Verlag, 2008. ISBN 978-3-8309-7018-7. URL https://books.google.de/books?id=l3GfZTYb9fcC.

Barbara M. Wildemuth, Chad Morgan, Songphan Choemprayong, Lili Luo, Carolyn Hank, Leo L. Cao, Carol L. Perryman, Laura Sheble, Kathy Brennan, Sanghee Oh, Leslie Thomson, Yan Zhang, Mary Wilkins Jordan, Kristina M. Spurgin, and Abe J. Crystal. *Application of social research methods to question information and libary science*. 2017.