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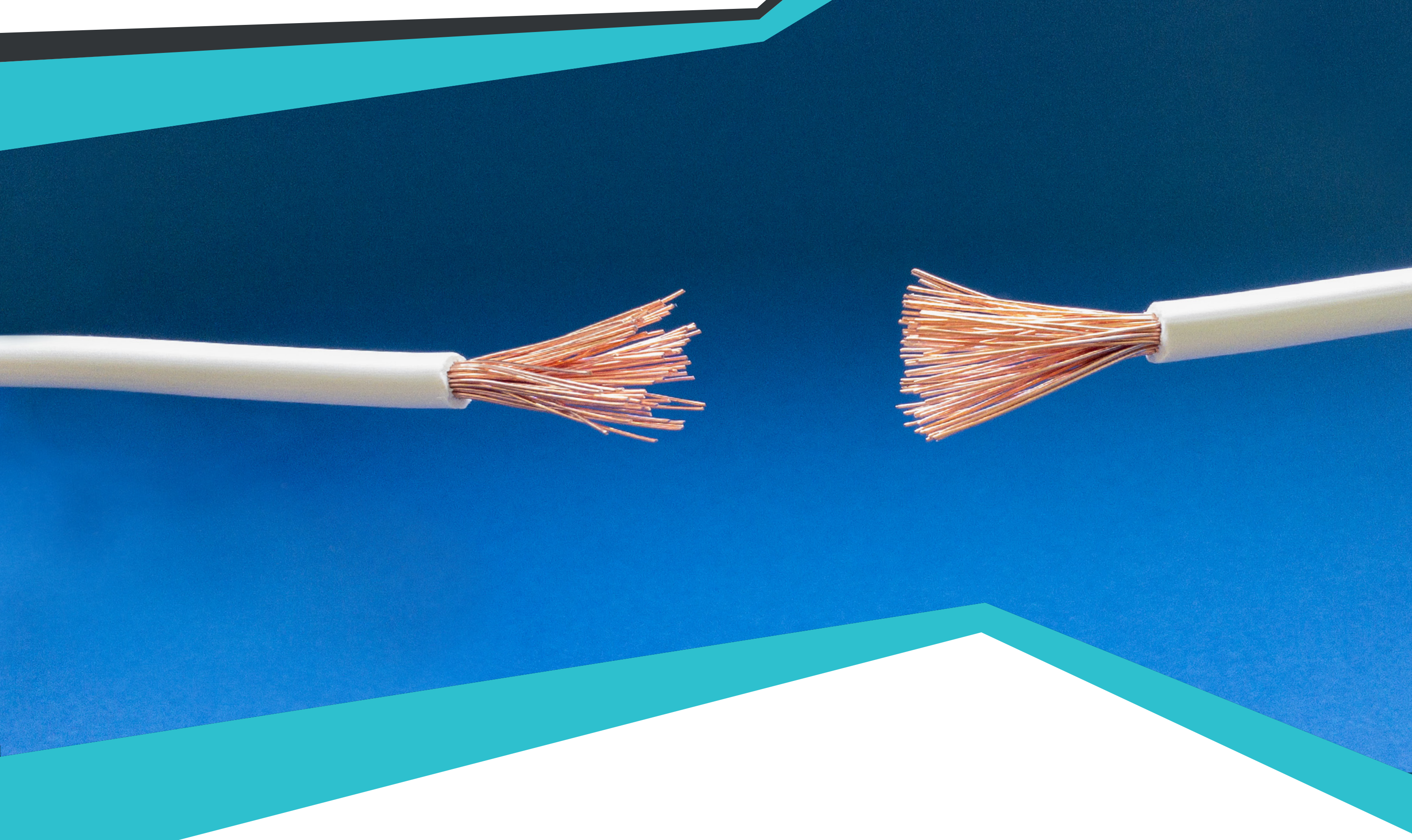

Engineering Students' Understanding of Basic Electric Circuit Concepts and the Effect of Qualitative Worksheets

Dion Timmermann

ENGINEERING EDUCATION RESEARCH
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ENGINEERING STUDENTS' UNDERSTANDING OF BASIC ELECTRIC CIRCUIT CONCEPTS AND THE EFFECT OF QUALITATIVE WORKSHEETS

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SUMMARY

The systematic inquiry of students' conceptual understanding has enabled educators to move away from the assumption that students simply make random mistakes towards the realization that many incorrect answers given by students are based on internally consistent, albeit flawed, mental models. Helping students to overcome these flawed mental models often requires instruction that specifically addresses common misconceptions and uses active learning methods. Tutorial worksheets are research-based learning materials that support such instruction. They have been developed by several research groups world-wide. Most of the development and evaluation was focused on different physics courses and their curriculum.

This thesis provides a comprehensive overview of engineering students' understanding of basic electric circuit concepts, focusing on current and voltage in the context of simple circuits such as parallel and series connections as well as open and short circuits. It is found that the common misconceptions about electric circuit concepts that had previously been identified with students in physics courses also occur in engineering courses, albeit less frequently. The frequency of these misconceptions is shown to be reduced by the Tutorials *Current and Resistance* and *Voltage*. Using an approach that is informed by the Decoding the Disciplines framework as well as APOS-Theory, these Tutorials are analyzed and further refined.

Additional student difficulties and misconceptions that are related to concepts primarily taught in engineering courses are identified in this thesis. Most prominently, the voltage across an open switch is found to be a critical test for students' understanding of Kirchhoff's Voltage Law. Of more than 5500 students, 52% believed the voltage across an open switch to be always zero. A Tutorial that uses the electric potential to address this misconception is documented and evaluated, showing that the electric potential can be an effective tool in helping students overcome their misconceptions about voltage.

Using threshold concept theory, the importance of the concept of the electric potential is underlined, adding another argument why it should be considered a corner stone of instruction on DC circuits.

This thesis is the first German dissertation on university-level electrical engineering education research. To characterize its relation to international discipline-based educational research as well as educational research in Germany, the thesis contains an extensive introduction to the theoretical frameworks, methods, and methodology that inform it and the work of the Engineering Education Research Group at Hamburg University of Technology.

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1 INTRODUCTION

It is not uncommon to think of teaching as an art. After all, many good teachers have the qualities of an entertainer. They do not simply stand in front of students and talk at them, but bring life to the curriculum, guide students to envision relations in complex subject matter, and create a personal connection between it and their students. However, contrary to what this belief might imply, teaching is not a talent a person is born with or without, but something that can be understood through research (see e. g. Chapter 3). Building instruction based on such research can help even inexperienced instructors achieve higher learning-gains and engagement than experienced instructors (Deslauriers et al., 2011).

The author has met many engineers that are content with the state of engineering education. They often fondly remember their years at university and feel that they have received good education. The author himself feels the same way about his years at university and the education he received. However, the low retention rate of engineering students indicates a flip side of the coin. Only about 50% of the students that enroll in an engineering degree in the USA (Geisinger and Raman, 2013), Australia (Godfrey et al., 2010), and Germany (Wolf, 2017, p. 18f) finish their degree. Thus, for every successful graduate, there is one student who dropped out. While there certainly are good reasons to not finish a university degree spanning multiple years, the author believes that improvements in engineering education, such as research based instruction, can increase retention rates and improve learning of all students while sustaining or increasing the current level of engineering education. This thesis aims to contribute to the research required for research-based instruction and improve the understanding of student learning.

In particular, this thesis provides a comprehensive overview of students' understanding of basic electric circuit concepts, focusing on current and voltage in the context of simple electric circuits such as parallel and series connections as well as open and short circuits. While these concepts might seem trivial compared to many of the other concepts covered in an electrical engineering curriculum, they are of utmost importance, as they form the basis for almost every concept in electrical engineering. The findings on student understanding presented in this thesis can help to further improve electrical engineering education. They highlight the aspects most troublesome for students and thus can be used to determine the parts of instruction that should be improved most. They can also be used for the development and refinement of educational materials, some of which are investigated, extended, and discussed as part of this thesis.

The following section will further specify the goal of this research project and detail the research questions this thesis addresses. The subsequent section will provide an overview of the thesis as a whole and highlight parts that are most important for readers not familiar with educational research.

1.1 GOAL AND RESEARCH QUESTIONS

The identification of student misconceptions has allowed educators to move away from the belief that students simply make random mistakes towards the realization that many incorrect answers given by students are based on internally consistent, albeit flawed, mental models. In turn, research-based instruction and instructional materials have been developed that aid students to change their mental models by specifically addressing their difficulties with and misconceptions about subject matter.

Mental models and conceptual change are introduced in Sections 2.3.1 (p. 15) and 2.3.2 (p. 17).

For the concepts of current and voltage, many student difficulties and misconceptions have been identified and described by the physics education research (PER) community. This research has been the basis for many improvements in student learning of these concepts. Most of it was carried out with students in the context of physics courses. While it might seem likely that students in engineering courses have the same difficulties and misconceptions with these concepts, there only is limited data available. To fill this gap, the first research question is:

RQ 1 What are engineering students' conceptual difficulties with current and voltage?

This question will be answered in two steps: Firstly, by testing if what is already known about student understanding in physics courses is also true in engineering courses. Secondly, by investigating concepts related to current and voltage that are addressed in engineering education but rarely in physics education. These two steps result in the following two research questions, which are mainly addressed in Chapter 7:

RQ 1A Are the conceptual difficulties with current and voltage identified in physics courses also prevalent in engineering courses?

RQ 1B Are there conceptual difficulties with current and voltage in the electrical engineering curriculum that have not been identified before?

To help students overcome their conceptual difficulties, different instructional methods have been developed. One such method are the

Tutorial Worksheets, or *Tutorials* for short, developed by the Physics Education Group at the University of Washington. The *Tutorials in Introductory Physics* (McDermott and Shaffer, 1998, 2002, 2012) cover some aspects of electrical engineering and have been translated into several languages (e. g. McDermott and Shaffer, 1997, 2008, 2009, 2011). Especially relevant for the understanding of current and voltage are the Tutorial Worksheets *Current and Resistance* as well as *Voltage*. While the effect of these Tutorials has been tested and evaluated with students in physics courses (McDermott and Shaffer, 1992), there exist limited data on their effectiveness in the context of engineering education. The different approach to subject matter that is often taken in engineering courses compared to physics courses could after all affect the impact of the Tutorials or result in conceptual difficulties not addressed by the Tutorials. Therefore, the second research question arises:

The concept of Tutorial Worksheets is described in Section 2.3.4 (p. 26).

The use of Tutorials is described in Section 4.3 (p. 57).

For the full Tutorials, see Appendices B.1 (p. 309) and B.4 (p. 331).

RQ 2 To what extent can the conceptual difficulties identified before be overcome through the use of existing Tutorial worksheets?

Again, this question is broken down into two sub-questions: Firstly, the change in the frequency of incorrect answers can be measured. Secondly, the Tutorials can be investigated to ensure that all relevant concepts are addressed:

RQ 2A To what extent is the frequency of the conceptual difficulties reduced when existing Tutorial worksheets are used?

RQ 2B Are there relevant conceptual difficulties that are not addressed by the existing Tutorial worksheets?

RQ 2A is addressed in Chapter 7, RQ 2B is addressed in Chapter 8. In Chapter 7, it is found that many students have conceptual difficulties with Kirchhoff's Voltage Law, especially in the context of open circuits. They for example believe the voltage across an open switch to always be zero. Chapter 9 discusses why the electric potential might help students to overcome this misconception and analyzes how far Tutorial worksheets using the electric potential can help students overcome it. This investigation is framed by the third research question:

RQ 3 To what extent can an improved understanding of the concept of electric potential help students overcome specific conceptual difficulties with voltage?

Chapter 10 adds a qualitative analysis regarding this question, discussing why the electric potential might be more important than other concepts in a typical electrical engineering curriculum.

1.2 STRUCTURE OF THIS THESIS

This thesis covers many different concepts from the field of basic circuit analysis. In addition to these, it also discusses and uses serval concepts from engineering education research. The thesis is intended to be read by researchers and educators who work in the field of electrical engineering education. As these readers can be assumed to have at least some background in electrical engineering, its fundamentals are not repeated in this thesis. However, the core explanatory frameworks and research methods from discipline-based educational research that are used in this thesis are introduced in various chapters, as not all readers are assumed to be familiar with all of them. At the same time, these background chapters are intended to help readers familiar with educational research to determine the author's interpretation of the used frameworks, methodology, and research methods.

Discipline-based educational research is defined in Section 2.1 (p. 9).

The following overview of the thesis will highlight parts that could be particularly helpful for readers less familiar with educational research. However, due to the multitude of backgrounds different readers will have, they are encouraged to decide on their own which chapters and sections to focus on.

The thesis is divided into three parts, which are entailed by an appendix.

Background

The first part of the thesis consists of four chapters that cover different aspects which are fundamental to this work.

Chapter 2 (named *Explanatory Frameworks*) presents three different frameworks that explain and provide methods to investigate student difficulties. By far the most important of these frameworks is the conceptual change theory described in Section 2.3. While the theory itself is fairly abstract, the idea of student misconceptions defined and described in Section 2.3.3 is vital for understanding this work. Tutorial Worksheets, which are central to this thesis, are defined in Section 2.3.4. That definition, however, is quite technical and mostly describes what Tutorials are. How they are applied, is described in Section 4.3 (see below).

Chapter 3 (*Prior Research*) gives an overview of the state of the art of those parts of engineering education research that are relevant for this research project. The chapter is meant to provide a broad picture. Individual results from prior research that are relevant for the interpretation of data in other chapters are reported in the respective chapters.

Chapter 4 (*Context of the Investigation*) describes the courses this research project was conducted in. The chapter consists of an overview of the characteristics of university courses in Germany and a detailed description of the individual courses. The use of Tutorials in these courses is described in Section 4.3.

Chapter 5 (*Methodology & Methods*) describes the general approach to research used in this thesis as well as individual research methods.

Contributions to Research Methods, Empirical Evidence, and Analysis

The second part of this thesis contains its main contributions to engineering education research. Research methods that were developed and refined as part of this thesis are presented in addition to student data answering the research questions.

Chapter 6 (*Extension of Educational Research Methods*) presents two research methods that have been developed or refined as part of this research.

Chapter 7 (*Student Understanding of Current and Voltage*) is the first "typical" results chapter. It describes several tests that were used to investigate different aspects of engineering students' understanding of current and voltage in the context of different circuit configurations. The chapter answers research questions RQ 1A, RQ 1B, and RQ 2A. Notable for later parts of the thesis are the findings on students' understanding of the voltage across open circuits presented in Section 7.4.

Chapter 8 (*Content-Focused Analysis of Tutorials and APOS-Theory in Electrical Engineering*) presents an analysis of the Tutorials *Current and Resistance* as well as *Voltage*. Several improvements to the Tutorials are presented. The chapter answers research question RQ 2B.

Chapter 9 (*The Electric Potential in Basic Circuit Analysis*) discusses why and how the electric potential can be used to help students overcome difficulties with voltage, especially that across an open circuit. Section 9.6 describes the development of a Tutorial on the electric potential and its evaluation using pre- and post-tests. This chapter answers research question RQ 3.

Interpretation

The third part of this thesis contains two different approaches to summarize the findings reported in the previous part.

Chapter 10 (*Current, Voltage, and Potential in the Context of Threshold Concepts*) offers an interpretation of the results on students' understanding of current and voltage using threshold concept theory. Threshold concepts represent a fourth explanatory framework that – unlike the ones presented in Chapter 2 – is purely qualitative.

Chapter 11 (*Summary & Conclusion*) summarizes the findings for each research question. The chapter also offers a more traditional interpretation of the results in the context of the prior research and provides an outlook on future research questions.

Appendix

The appendix provides different pieces of information that complement the data in the main part of the thesis.

Appendix A (*Overview of Tutorials, Tests, and Interviews*) lists the different cohorts that the data for this research project was gathered in. It details at what points in the semester Tutorials were used and tests and interviews were conducted.

Appendix B (*Tutorials*) presents the Tutorials used in this thesis in full. The German versions used in instruction in the German university courses are printed next to the English translations.

Appendix C (*Intended Observations and Inferences of Tutorials*) lists the Intended Observations and Inferences (IOaI) of different versions of the Tutorials *Current and Resistance* as well as *Voltage*. The development of the IOaI is discussed in Section 8.1.

Appendix D (*Preliminary Genetic Decomposition of Tutorials*) presents a preliminary genetic decomposition of different versions of the Tutorials *Current and Resistance* as well as *Voltage*. The preliminary genetic decompositions are discussed in Section 8.5

Appendix E (*Tests*) lists the German original and English translation of all the tests used in this thesis.

Appendix F (*Interviews on Electric Circuits and their Representations*) describes a series of ten semi-structured interviews. Excerpts of these interviews are used in Chapters 7 and 8.

BACKGROUND

2 EXPLANATORY FRAMEWORKS

There are many different frameworks that provide theories to explain how students learn and what can be done to improve their learning. The different explanations of learning result in differences in the way researchers investigate learning and thus differences in the research methods they employ. Consequently, it is prudent to specify the frameworks that inform a piece of research.

This chapter starts with an introduction to discipline-based educational research (DBER). For all intents and purposes, DBER is a field of research. However, its core idea that *learning can and should be investigated by looking at the discipline-specific aspects of learning* has a fundamental influence on the way learning is understood and investigated by researchers in that field. Following this introduction to DBER, three different theories of learning are discussed and compared. Their different interpretations of *what learning is*, lead to vastly different understandings of the investigation of learning. Finally, three frameworks will be introduced that are fundamental for the research reported in this thesis. They focus on three different aspects[1]: (1) how students (mis)understand a concept, (2) how experts understand and teach it, as well as (3) the subject-matter itself. A fourth framework will be introduced and discussed in Chapter 10.

There is a large number of other frameworks used in engineering education research, some of which focus on completely different aspects of teaching and learning, like problem solving skills, assessment, psychological aspects of learning, as well as students' attitudes and beliefs. For a recent review of approaches used in physics education research, which largely overlap with the ones used in engineering education research, the review by Docktor and Mestre (2014) is recommended.

2.1 DISCIPLINE BASED EDUCATIONAL RESEARCH

This thesis is firmly located in the field of discipline-based educational research (DBER). DBER is the collective term for all branches of educational research that focus on education in a specific discipline. While there are many similarities between the different branches, there are also differences in focus and methods. Two branches of DBER are relevant to this thesis: Engineering education research (EER) and physics education research (PER). As this thesis is on engineering ed-

1 C. Kautz, personal communication

ucation, it is part of EER. PER is relevant for this thesis as it strongly influenced the research presented in this thesis.

As reported by the National Research Council (2012), DBER tries to (1) understand how students learn concepts, practices and ways of thinking in the respective disciplines, as well as (2) identify appropriate learning objectives and instructional approaches in the respective disciplines and measure if these objectives are reached by students. The results of such research (3) provide the basis for the subsequent development of materials and methods for instruction. DBER also covers (4) the understanding of the nature and development of expertise in the respective disciplines and (5) the identification of approaches for making the education in the respective disciplines more broad and inclusive. Aspects (1-3) also are goals of this thesis, while aspects (4-5) are not covered here.

DBER has considerable overlap with the Scholarship of Teaching and Learning (SoTL), as both investigate student learning and teaching. Scholars in SoTL, however, are mostly teachers that investigate their own courses and use their findings to successively improve their teaching. In publications, they report on their findings to share their insights and engage in a discussion on the teaching of their subject. DBER researchers, in contrast, tend to investigate other instructors' courses or do larger longitudinal or lateral investigations spanning multiple years or courses. Their publications aim to be generalizable. This comparison by no means aims to diminish the accomplishments of SoTL. While DBER researchers primarily research the education in one discipline, many SoTL instructors not only investigate their own teaching, but also are professional researchers in the fields they teach (c. f. National Research Council, 2012, pp. 11-12). The National Research Council (2012, pp. 12) also notes that DBER researchers predominantly publish in discipline-specific journals, while SoTL scholars mostly publish in interdisciplinary journals focused on teaching or SoTL in general.

While DBER has some overlap with research in educational psychology and on higher education ('Hochschuldidaktik' in German), there is an important difference in its focus. While all three fields address learning and teaching at university, subject specific aspects are only secondary in educational psychology and higher education research while they are of primary interest in DBER (National Research Council, 2012, p. 12). Consequently, research in DBER requires knowledge in not only educational research but also the respective discipline under investigation. Sometimes, this knowledge is split among different individuals in a team; in other cases, one researcher is trained in both fields (National Research Council, 2012, p. 2).

In his introduction to PER, Beichner (2009) distinguishes two branches of research, which can also be found in EER: *Basic research* in PER and EER investigates "what happens as students struggle to grasp and use concepts" (Beichner, 2009, p. 3), i. e. it catalogues common problems in student understanding as well as their frequency and identifies the specific reasons for each problem. *Applied research* in PER and EER uses the results of basic research to improve instruction. This is often done in an iterative process, based on measurements of student learning. Beichner (2009) notes that there is a growing number of researchers whose work does not fit in any of these two categories. These researchers investigate topics that are not discussed in this thesis, such as socio-cultural issues.

This thesis engages in basic and applied EER research. Specifically, it uses conceptual change theory and the more detailed student misconceptions framework as a basis for its basic EER research. Tutorial worksheets are refined and developed as part of its applied EER research.

Three explanatory frameworks that are used in DBER are introduced in Sections 2.3, 2.4, and 2.5. Most important for this thesis is the framework of conceptual change theory, introduced in Section 2.3.

2.2 THEORIES OF LEARNING

In the following, three fundamental theories of learning will be described and compared: Behaviorism, Cognitivism, and Constructivism. These theories present three distinct descriptions of learning and call for different ways of teaching. Each theory was dominant in the educational community at some point since the middle of the last century. All three theories seem to be tightly interlocked with ideologies on how learning and thus education should *be*. Many educators can attest that discussions about these theories easily lead to heated arguments. Therefore, it is important to remember that these three theories are not mutually exclusive but rather different ways to look at the same thing: learning. Subscribing to one of these theories does not require the rejection of all aspects of the other theories.

2.2.1 *Behaviorism*

Behaviorism is the oldest of the three theories presented here with the well known behavioral theories of *classical conditioning* developed by Pavlov in the 1920s (Schunk, 2012, pp. 78-84) and *operant conditioning* developed by Skinner in the 1930s (Schunk, 2012, p. 88). Behaviorism was the dominant learning theory until the 1950s (Ertmer and Newby, 1993).

Behaviorism treats the learner as a black box, with the environment being its input and the learner's behavior its output. Learning is defined as a change in form or frequency of the learner's behavior (Ertmer and Newby, 1993), i. e. the learner becoming able to do something or doing something more often. The existence of internal factors like the learner's mental models, thoughts, beliefs, or feelings is not disputed, but intentionally excluded from the theory. Even in 1985, Skinner argued that the human brain and mind were simply not understood well enough and that treating them as part of a black box would be more productive.

While names like Pavlov and Skinner may remind one of simple and possibly cruel animal experiments, behavioral learning theories can be used to describe the learning of complex tasks. Skinner (1985) for example describes how learning to drive a car can be explained by behaviorism. At the beginning, the learner receives verbal stimuli from their driving instructor. These are pieces of advice and rules which govern the learner's behavior of flipping switches, pushing pedals and turning the wheel. When gaining experience, the environment becomes the dominant stimulus for the learner. The consequences of what happens when the learner turns the wheel or pushes a pedal change and reinforce the learner's behavior. In most situations, the learner does not anymore follow the rules they were once told, but instead uses a trained stimulus-response behavior.

In the opinion of Schunk (2012), behaviorism seems to best explain the learning of associations, like the multiplication of small numbers or the meaning of words in a foreign language (p. 25). Skinner's example of learning to drive a car shows that behaviorism is also suited to describe how even complex cognitive processes can become "automated", like how the manipulation of equations can become an almost mindless task after years of practice.

2.2.2 *Cognitivism*

Cognitivism became the dominant learning theory in the late 1950s (Ertmer and Newby, 1993). Cognitivist theories see internal factors like the learner's attitudes and beliefs, but also how learners process information and create mental structures as the most relevant factors in learning (Schunk, 2012, p. 22). Successful learning is the acquisition of knowledge and skills (Ertmer and Newby, 1993). Empirical investigations of learning with cognitivist theories are much more difficult than with behavioral theories, as relevant parts of the learning process cannot be observed directly, but must be inferred through questions and tests.

There is a wide array of cognitive learning theories that address many different aspects of learning. Social cognitive theories address the importance of a learner's goals, the outcomes they expect, as well as their self-efficacy (Schunk, 2012, p. 160). Researchers working on social cognitive theories also investigate tutoring and mentoring scenarios (Schunk, 2012, p. 158f.). There are also cognitive theories that see learning as *information processing*, with the brain behaving similar to a computer. To an extent, such theories are a continuation of the work on knowledge retention by Ebbinghaus (1885). They for example address the role of and difference between short-term and long-term memory. Another such theory that is frequently used is the cognitive load theory, which posits that a brain can only handle a limited amount of processing at once (Schunk, 2012, p. 223).

Schunk (2012, p. 25) remarks that cognitivism seems to be appropriate for describing the learning of complex tasks, like the solving of engineering problems, or text analysis.

2.2.3 *Constructivism*

Constructivism became dominant in the 1990s (Ertmer and Newby, 1993). It is a branch of cognitivism, as it also sees learning as an internal process. However, due to its fundamental differences to cognitivism, it is usually listed as a separate theory (Ertmer and Newby, 1993). Schunk (2012, p. 230) notes that technically constructivism is not a theory of learning, but a theory of knowledge. It effectively being separated from other cognitivist theories by its specific philosophy of knowledge might explain the sometimes heated debates between "constructivists" and "cognitivists".

Constructivism gets its name from the idea that learners not simply "receive" information about the world and "store" it in their minds, but instead actively *construct* their understanding. Cognitivist theories describe the conditions necessary for new mental structures to form. The learner must have the necessary foundation on which these new mental structures can stand. They must have the necessary prerequisite knowledge so that the newly taught ideas are understandable and make sense to them. Instruction must be designed to account for different levels of pre-knowledge learners might have. The constructivist idea that learners actively construct their mental structures does not merely mean that they must be active participants in the learning process, but also presents a further requirement for the formation of mental structures: A learner must not only have the foundation necessary for the construction of a new mental structure, but must not have any mental structures in place that *block* the construction of new ones, because they for example already explain the new concept in a different (simpler or scientifically incorrect) way. Using the image of knowledge being constructed out of individual pieces, like Lego bricks that form building, cognitivism stresses that every new piece requires other pieces that this new one can be put on, while constructivism also posits that there must be no other (incorrect) piece at the location the new one is supposed to be placed.

Constructivist learning theories criticize *traditional teaching* and instead strongly favor *active learning* (e. g. Schunk, 2012, p. 276). Traditional teaching is a form of teaching that was dominant in universities at least until the 1990s, but very likely still is today. In traditional teaching, instructors present information and give examples of how to solve problems. With active learning, students are more engaged in the learning process (Prince, 2004). Students are for example asked to collect data, make observations, generate and test hypotheses, or simply work in groups. These activities are better suited to the mental tasks students perform when learning.

For behaviorism and cognitivism, clear examples could be shown where the respective theory offered a good description of the learning process. Most researchers seem to be much more cautious to describe situations where constructivism is best suited, likely because it has no hard border to cognitivism. However, it is commonly stated that constructivism is well suited for fields and situations with ill-structured knowledge (e. g. Ertmer and Newby, 1993). These could either be fields where no optimal solution or answer exists (e. g. the debate of social issues) or where information is not available in a structured or complete manner (e. g. doctors interacting with a patient to diagnose them). Such situations with no optimal solution also occur in engineering when for example during the design of a product trade-offs have to be made between the product's safety and its usability. A lack of usability could result in customers to prefer a competitive product that is more usable and less safe. Situations with incomplete or unstructured information regularly occur when design decisions have to be made early in a product's development, long before all of their consequences are known.

2.2.3.1 *Radical, Social, and Pedagogical Constructivism*

There are many different variants of constructivism, most notably *radical* and *social* constructivism. Radical constructivism posits that no objective reality exists outside of the mental constructions of one's mind (Schunk, 2012, p. 231). Based on this theory, there is no objective, shared reality. Social constructivism sees knowledge as a social construct that is negotiated between individuals (Ben-Ari, 2001). Ben-Ari (2001) warns, that if taken to their extremes, the ideas of radical and social constructivism can lead to the rejection of ethics or an objective truth.

This thesis is not interested in such extreme interpretations or the "details of epistemological psychology" (Matthews, 1997, p. 4). Instead, it limits itself to the core idea of constructivism, learners actively constructing their own knowledge (see above), and uses this idea to analyze students' conceptual understanding and the development of educational materials. Matthews (1997) labels such a stance as *pedagogical constructivism*.

2.2.3.2 *Perspectives of Constructivism*

Schunk (2012, p. 232) notes that constructivism also has different *perspectives* that he aligns on a spectrum.

Exogenous constructivism, on one end of the spectrum, "refers to the idea that the acquisition of knowledge represents a reconstruction of structures that exist in the external world" (Schunk, 2012, p. 232). This theory aligns with the theory of conceptual change by Posner et al. (1982), introduced in Section 2.3.1 – even though Posner et al. do not base their theory on constructivism.

Endogenous constructivism lies on the other end of the spectrum. It is based on the idea that "[m]ental structures are created from earlier structures, not directly from environmental information; therefore, knowledge is not a mirror of the external world [..., but] develops through the cognitive activity of abstraction and follows a generally predictable sequence" (Schunk, 2012, p. 232). Schunk considers the well known theory by Piaget (1970) to be an endogenous constructivist theory. Consequently, APOS-Theory (introduced in Section 2.5.1) is also an endogenous constructivist theory, as it is based on Piaget's work.

2.3 CONCEPTUAL CHANGE THEORY, MISCONCEPTIONS, AND TUTORIALS

In the following, conceptual change theory or rather different theories of conceptual change will be described. All of these theories can be considered to be constructivist theories in the field of DBER. The much more focused concept of student misconceptions will be introduced later, as well as Tutorials, a form of instruction designed to combat misconceptions.

2.3.1 *The Conceptual Change Theory by Posner et al. (1982)*

Conceptual change theory, as used in this thesis, has its origins in Thomas Kuhn's work on the change of scientific knowledge (Posner et al., 1982). In his book *The Structure of Scientific Revolutions*, Kuhn (1970) argues that new scientific theories are not always simple additions to existing theories, but can at times require the rejection of previous theories. Posner et al. (1982) applied these ideas to learning.

According to the conceptual change theory as described by Posner et al. (1982), all learning has to be seen in the context of the learner's current understanding, called their *conceptual ecology*. When a learner makes a new observation or is taught a new concept, this new observation or new concept can align or conflict with their conceptual ecology. If the new observation or concept aligns with their conceptual ecology, a process called *assimilation*[2] takes place. The new knowledge can simply be integrated into the learner's previous understanding, thereby extending their conceptual ecology. If the new observation or concept conflicts with the learner's conceptual ecology, they experience an *anomaly*. In order for the new observation or concept to be accepted, the learner's conceptual ecology must be changed in a process called *accommodation*[2]. Only thereafter, the new knowledge can be integrated into the learner's conceptual ecology.

Accommodation is performed neither quickly nor without resistance. Posner et al. (1982) list four conditions that must be met for it to take place:

1) THE LEARNER MUST BE DISSATISFIED WITH THEIR EXISTING CONCEPTIONS. They must have encountered one or more anomalies, i. e. problems that they were unable to solve or that caused contradicting or obviously incorrect results. Only then, will they be willing to accept major changes to their conceptions.

2) THE NEW CONCEPTION MUST APPEAR INITIALLY PLAUSIBLE. The new conception must solve the previously unsolvable problems or lead to non-contradictory, seemingly correct results. Also, the new conception must be consistent with the learner's other current conceptions – except for the one it replaces.

3) THE NEW CONCEPTION MUST BE INTELLIGIBLE. The learner must be able to understand the new conception. The famous analogy of mass bending space-time like a sheet of rubber is a good example how metaphors or analogies can be used to make abstract ideas intelligible.

4) THE NEW CONCEPTION MUST SEEM FRUITFUL. A new conception that satisfies the criteria above will be tested, i. e. used, by the learner. When these first uses of the new concept lead to new insights and deeper understanding, the new concept will become more compelling and its accommodation more likely. In the author's opinion, this condition characterizes concepts that are learned more readily, unlike the previous three conditions, which describe requirements for learning.

Posner et al. (1982) stress that accommodation is not the only possible result of a learner experiencing an anomaly. Rather than restructuring their conceptual ecology, they might also (1) reject the observation, (2) simply consider the observation to be irrelevant, (3) compartmentalize the new concept, i. e. only apply it under very spe-

2 The words *assimilation* and *accomodation* were introduced by Piaget. Posner et al. (1982) note that by using these words, they do not intend any commitment to his theories.

cific conditions, or (4) try to "forcefully" assimilate the new concept without accommodation. Educational research that is based on conceptual change theory has an abundance of examples that illustrate these cases. Instructional methods and materials based on conceptual change theory will try to minimize the likelihood of these four negative outcomes to happen, as e. g. described in Section 2.3.4.

Examples of compartmentalization are presented in Section 2.3.3.1 (p. 22).

2.3.2 *Other Theories of Conceptual Change*

The theory as presented above yielded insight into the reasonings for students' incorrect answers. Students gave incorrect answers not simply because they were unable or unwilling to absorb the correct understanding. Instead, incorrect answers were the result of consistent, albeit scientifically not accepted, theories that had proven useful to students and thus would not be replaced easily (see e. g. Brown and Hammer, 2013). "The work of Posner et al. (1982) became the leading paradigm that guided research and practice in science education for many years" (Vosniadou et al., 2013).

Strike and Posner (1992) later presented a revision of the theory, that changed three aspects: (1) The original theory had presented students' conceptions as similar to scientific theories. The revision acknowledged that students' conceptions could also be less well formulated or even non-verbal images of "how things work". (2) The original theory had seen students' conceptions as separate from their conceptual ecology, which was revised. Students' (mis)conceptions determine their view on the world, and thus act in the same way as their conceptual ecology. (3) Strike and Posner found their original theory to be "overly rational", due to its background in Kuhn's philosophy of science. In their revision, they acknowledge that not only rational thoughts affect conceptual change.

Other researchers also developed theories of conceptual change. While some of these try to describe how concepts are "stored" in a student's mind, others offer explanations why some concepts resist change more than others. Three theories that are relevant for this thesis are described in the following. Each theory is backed by extensive research. Since these three theories partially conflict with each other, there is a lively debate about the theories in the scientific community. The authors of the respective theories have criticized competing theories numerous times (see e. g. Vosniadou, 2013).

2.3.2.1 *"Framework Theory" Theory*

Vosniadou (e. g. 1994, 2013) proposes that starting at infant age, humans develop a *framework theory of naive physics*. This framework theory consists of *constraints* such as "solid objects can't move through each other" or "inanimate objects don't move on their own" (both examples from Brown and Hammer, 2013). In this context, the word 'theory' obviously does not mean a scientific theory, but a coherent system of such constraints (Vosniadou, 1994; Vosniadou et al., 2013). A learner is not consciously aware of their framework theory, and it does not directly affect their hypotheses about or answers to real-world problems.

Instead, the framework theory influences the development of *specific theories*. A specific theory essentially is the learner's understanding of a specific concept, the sum of all the knowledge they have acquired on that concept. When confronted with a specific situation, the learner spontaneously creates a *mental model* based on their specific theory. This mental model is a mental representation of reality. It can be used to "simulate" reality. Thus, when answering a physics question, a student creates a mental model which they would use to answer this question. This mental model is based on their specific theory that is relevant to the question, which in turn is based on their framework theory relevant for that specific theory. At least some mental models are created spontaneously each time they are used. Due to this repeated spontaneous creation, a learner's mental model can change from question to question. Successful mental models might, however, also be stored in memory (Vosniadou, 1994).

Effectively, the "framework theory" theory presented here is a three layer model of understanding. When a learner thinks about a problem in for example an engineering course, they create a mental model. This mental model is based on a specific theory, of which they have one for each topic in the realm of the physical world. All of these specific theories are based on their framework theory of physics. Vosniadou et al. (2013) states that similar combinations of specific and framework theories exist for the realms of psychology (physical objects that are alive), mathematics, and language and that it is much easier to make modifications to the specific theories than to the underlaying framework theories. She also stresses that framework theories are coherent systems that are very resistant to change due to their internal consistency and age.

According to Vosniadou et al. (2013), specific theories are mainly formed through an additive process. When a learner observes something, they interpret this observation based on their framework theory. They then add this interpretation to their specific theory. This interpretive process, however, can result in inconsistent knowledge or misconceptions. Vosniadou (1994) describes for example *synthetic models*, a type of misconception, where the learner integrates new information into their incompatible specific theory. An extreme example of such models is described in Section 2.3.3.1, where students show a disconnect between what they know they were told in class about gravity and their incompatible beliefs concerning falling objects.

Vosniadou et al. (2013) stress that conceptual change takes a long time and recommends to account for this inevitability in curriculum design. They propose to not only introduce instructional activities that lay the ground work for conceptual changes that will happen in later years, but also to introduce concepts in a way that make later expansions to them more easy.

2.3.2.2 *"Knowledge in Pieces" Theory*

In contrast to the framework theory presented above, diSessa (1993) proposes that knowledge consists of many individual pieces, called *phenomenological primitives* or p-prims for short. These p-prims are "atomic" memory elements or ideas, like *Ohm's p-prim*, which represents the idea that "More effort implies more result; more resistance implies less result" (see diSessa, 1993). While this p-prim on its own cannot be used to describe a concept, it can when connected with other p-prims. Ohm's p-prim for example allows to connect an *agent* with its *impetus* against a *resistance* resulting in an *effect*. For an understanding of Newtons first law, a student might for example connect Ohm's p-prim with p-prims about force as the impetus, mass as the resistance and acceleration as the effect, etc.

P-prims are the result of observations of the world, which are interpreted through the learner's current understanding, i. e. their current p-prims, as well as the connections and activation mechanisms of those. For novices, p-prims often are self-explanatory, something happens "because that's the way things are". When a novice becomes an expert, their p-prims become more strongly connected. Consequently, the reasons why "things happen" become more clear. With experts, p-prims are also activated more appropriately, i. e. experts are better in deciding which model to apply to a given situation.

2.3.2.3 *"Orthogonal Categories" Theory*

The theory of orthogonal categories described by Chi (2013) presents an explanation why some concepts are more resistant to change than others. Chi distinguishes between two kinds of incorrect knowledge: knowledge that is *inaccurate* and knowledge that is *incommensurate*. Inaccurate knowledge is "only" incorrect regarding the value, but not the *dimension* of that value. Incommensurate knowledge is incorrect in terms of dimension. 'Value' and 'dimension' in this context must not be interpreted as in mathematics, but rather as any *answer* and any *category of an answer*.

The difference between inaccurate and incommensurate can be illustrated using examples from the context of this work. The belief "at a junction current splits into equal parts" is incorrect, as the current splits depending on the resistance of each of the branches. The value (equal parts) is incorrect, but the category (current splits at junctions)

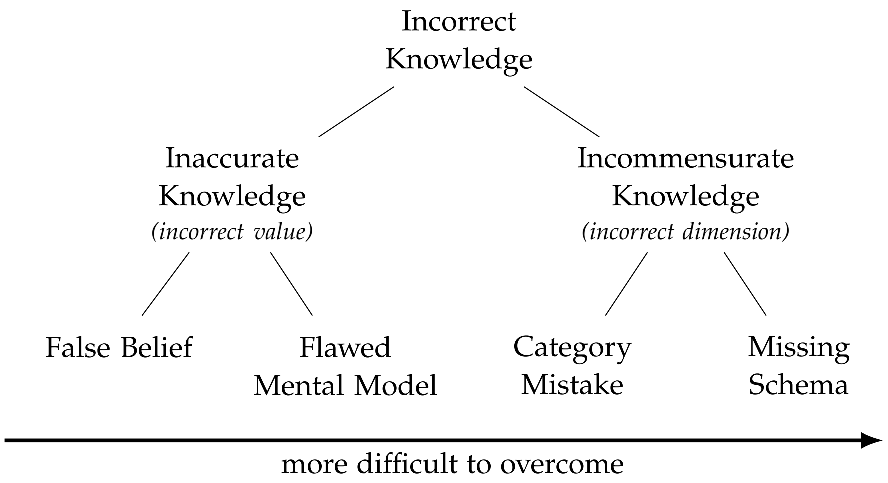


Figure 2.1: Relation of different kinds of incorrect knowledge in the theory of orthogonal categories.

is correct. Thus, the statement shows inaccurate knowledge. The mistaken answer "bulbs use up some of the current and thus cause subsequent bulbs to glow dimmer" is also incorrect. Current is not "used up". However, not only the amount (some of the current) is inaccurate, but the dimension of the answer (current *can* be "used up") is also false. Consequently, this answer shows incommensurate knowledge. The belief "batteries behave like current sources" is incorrect, as batteries actually behave like voltage sources. As the category of the belief (batteries behave like some kind of source) is correct, it is inaccurate knowledge.

Chi (2013) further divides these two kinds of incorrect knowledge by their scope. Inaccurate knowledge can occur with a singular piece of information, a *false belief*, or be part of an interrelated system of concepts that in itself is consistent, a *flawed mental model*. Incommensurate knowledge can occur when the given answer is in an incorrect dimension even though the student is aware of the existence of the correct dimension, a *category mistake*, or when a student does not even know of the correct dimension, a *missing schema*. The relation of these two kinds and four sub-types of incorrect knowledge is visualized in Figure 2.1. According to Chi (2013), they are, in the order presented here, increasingly difficult to overcome. While false beliefs can in some cases even be overcome by simply telling a student the correct answer, flawed mental models require more effort to be overcome, by e. g. explicitly refuting the underlying assumptions. Category mistakes are even more difficult to resolve, as these categories are often defined early in life. Students must be aware of the alternative category and must be made to understand the need to reassign the concept to that category. Teaching students a missing schema, requires the most effort. These different kinds of incorrect knowledge can affect each other.

Chi (2013) suggests that many misconceptions (see next page) are the result of category mistakes, where students believe something to be an *entity* and not a *process*. Students for example see heat as an entity. They believe heat to simply be hot molecules or a substance on its own. This leads to the misconception that heat can be contained in the same way as any other physical object. These category mistakes have far reaching consequences, as entities have dimensions such as volume, speed, or color, while processes have completely different dimensions as "occurring over time".

But even when students have correctly understood something to be a process, their understanding can still be incorrect. Chi (2013) differentiates between processes that are *sequential* and processes that are *emergent*. Sequential processes have an identifiable agent and often are the result of local events that behave similar to the global pattern. Emergent processes, in contrast, have no identifiable agent and can have local events that behave contrary to the global pattern. Chi (2013) names water flowing downhill as an example for a sequential process. The acting agent are the water molecules which push on molecules in the area below them, which in turn push other molecules further down. The local direction of movement largely corresponds to the global movement. She names *heat flow* as an example for an emergent process. There are no "heat particles" that move, i. e. there is no agent in the heat flow. Instead, molecules distribute their kinetic energy (i. e. heat) to other nearby molecules through collisions, which in turn transfer their energy. The direction of movement of the individual molecules is random and does not correspond with the direction of the heat transfer. Chi (2013) suggests that many students lack the category of emergent process. Because of this missing schema, they incorrectly believe many processes to be sequential.

2.3.3 *Misconceptions*

Several of the conceptual change theories presented above describe how existing knowledge can hinder the acquisition of new knowledge. This effect is encased in the idea of a misconception. There are several different definitions for misconceptions (see e. g. Wandersee et al., 1994). In this thesis, the definition by Hammer (1996) will be used. According to him, misconceptions

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

In particular that means:

Misconceptions are *stable cognitive structures*, i. e. an individual's mental structures or beliefs that have not changed over time, even though they might have been employed frequently. Thus, the outcome they predicted must have aligned with what the individual observed. Otherwise, the resulting anomaly would have resulted in the individual's dissatisfaction with the existing mental structure and likely caused it to change. A student might, for example, believe that "a body upon which no force acts will always come to rest". This student likely formed this belief early in their life, based on everyday experiences, like the observation that objects given an initial push across the floor – even balls – always come to rest. The student likely never experienced a situation without a hidden resistant force, such as air resistance. If cognitive structures are successfully employed on a regular basis, it is no wonder, they are *strongly held*. If the student mentioned above, for example played billiards regularly, they will not only believe "a body upon which no force acts will always come to rest", but also be able to reliably estimate the distance after which a billiard ball that they have hit will come to rest, further reinforcing the misconception.

Misconceptions also *differ from expert conceptions*, from the scientific consensus of the community, and in some cases are objectively incorrect. Overcoming misconceptions is therefore part of a novice's path to becoming an expert, by aligning their conceptions with those from others in the expert community.

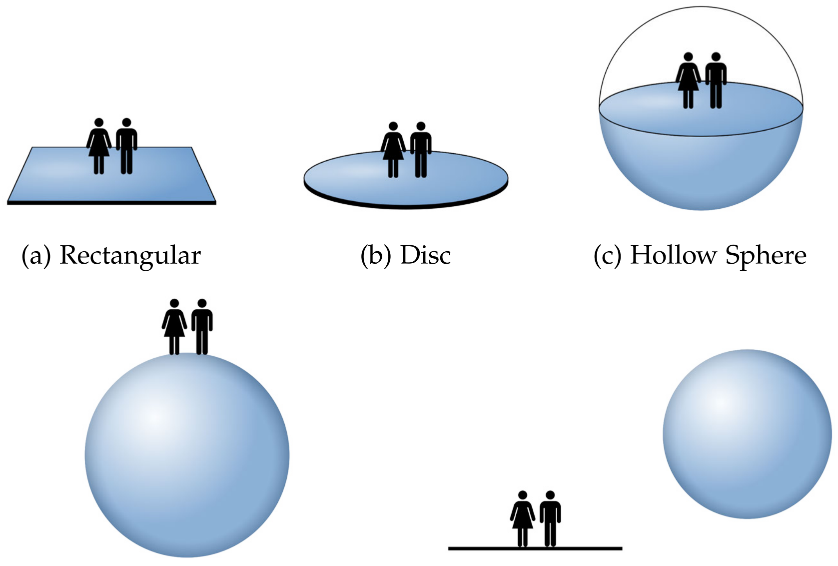
Further, misconceptions *affect in a fundamental sense how students understand natural phenomena and scientific explanations*. Consequently, a conception is only considered a misconception by this definition, if it it has an *effect on the student's understanding* and their *scientific explanations*, as for example in answers to exam questions. The conception must be of consequence.

Finally, Hammer (1996) states that misconceptions *must be overcome, avoided, or eliminated for students to achieve expert understanding*. While certainly true, misconceptions are in many cases unavoidable consequences of learning. In practice one will always learn concepts that can be falsely applied to new situations. Consequently, many researches prefer terms that deemphasize a misconception being a mistake and emphasize it being part of the student's process and inevitable struggle in learning.

The use of the term 'misconception' is further discussed in Section *2.3.3.2 (p. 25).*

2.3.3.1 *Examples of Misconceptions*

To further illustrate misconceptions and their influence on learning, some examples will be discussed in the following. The first example is based on research on children's mental models of the earth, conducted by Vosniadou and Brewer (1992). They catalogued different understandings of the shape of the earth and observed that "children



(a) Rectangular (b) Disc (c) Hollow Sphere

(d) Sphere (e) Dual Earth

Figure 2.2: Mental models of the earth. Concepts and depictions based on Vosniadou and Brewer (1992).

try to assimilate the information that the earth is a sphere with their preexisting knowledge structures in a way that allows them to retain as many of their presuppositions [misconceptions] as possible." Consequently, the accommodation of their presupposition, i. e. the belief that the earth is flat, is resisted as much as possible, resulting in only small corrections of the model or even a synthetic model.

Based on this research, a hypothetical child might, for example, start with a flat mental model of the earth, as from its everyday experience, the earth obviously is flat. All objects that the child knows do have boundaries. Thus, the earth must also have boundaries. The child might, for example, assume the earth to be rectangular (Figure 2.2a). When it gets told by adults, that "the earth is round", it assimilates this new information in its mental model. However, while the adults mean 'round' as *spherical* (Figure 2.2d), the child interprets 'round' as *circular*, resulting in the disc earth model (Figure 2.2b). This is the model that requires the least change but still incorporates the idea of "round". When the child is then told that the adults actually mean *spherical*, the child's mental model might change to the hollow sphere model (Figure 2.2c). In this model, the earth consists of a lower sphere with a flat surface on which people live and an upper sphere with the sky covering the earth like a dome. The hollow sphere model requires minimal change to the child's mental model, but still incorporates the idea of "spherical". Only once this hypothetical child has understood that large spheres can appear to have a flat surface and that due to gravity, people can stand on each point of that surface, it can accept the correct sphere model (Figure 2.2d).

INTERVIEWER: [1m:31s] Tell me about how the gravitational force on this [black 5 kg] ball compares to the gravitational force on that [approx. 620 g basket]ball. [...]

STUDENT: [2m:17s] The gravitational force on both of these balls is the same.

INTERVIEWER: Is that what you actually believe?

STUDENT: No. [...] I believe it should be more on this [black ball], simply for the fact that this is heavier. [...] Intuition tells me that it should be more, but after learning physics, we learned that it is actually the same.

Figure 2.3: Except of an interview on gravitational forces from Veritasium (2011).

Not every child will go through all the mental models described above. Some children skip some of the models or use ones not listed here. However, the general pattern is universal: Mental models, or concepts, are changed only when required and even then, the new information is viewed through the lens of the current mental model which can lead to unintended interpretations of the given information. As current models are usually assumed to be correct, changes made are as small as possible.

These incorrect interpretations and minimalistic changes can even lead to synthetic mental models (Vosniadou and Brewer, 1992), such as the dual earth model (Figure 2.2e). In this model, children believe there are two earths: The flat ground we live on and the spherical earth adults talk about. This split between reality and a "scientific reality" not only happens with children, as can be seen in the second example. In a series of video interviews, Derek Muller asked high school students to compare the gravitational force on two balls with different weight (Veritasium, 2011). Many of his interviewees were unsure or ambiguous about their answer. A relevant part of his interviews is transcribed in Figure 2.3. In the scientific model, the two balls have a different mass m but experience the same acceleration g

when falling. Consequently, the gravitational force $F_g = m \cdot g$ is different, even though they fall equally fast. The student shown in Figure 2.3 believes that a larger gravitational force acts on the heavier ball, but states that in school he learned that the force is equal. He might have mixed up the gravitational force and the free-fall acceleration (g). However, he was not able to solve the conflict between his observation (the ball feels heavier) and what he thought he learned in school. He gives two different answers, one he believes and one he thinks is correct. Such synthetic mental models could be considered the most problematic kind of misconception, as the answers students give are correct and thus disguise as correct understanding, while the students actually harbor a flawed mental model.

2.3.3.2 *Misconceptions are inevitable*

As the examples above indicate, misconceptions often arise from observations of the real world. As such, they practically are unavoidable when learning. Several of the theories introduced in Sections 2.3.1 and 2.3.2 offer explanations for this effect: Based on the theory proposed by Posner et al. (1982), new information is always interpreted through the learner's conceptual ecology, i. e. their current understanding. When a learner observes a phenomenon they have never seen before, two relevant scenarios can lead to a misconception. Either accommodation takes place and the learner is simply not aware that this new observation or their understanding of it is in conflict with their current understanding, or assimilation takes place, but the new conception simply does not align with an expert's conception. The learner would be aware of neither. Basically, the same argument can be made based on the theory of framework theories by Vosniadou et al. (2013). Another argument can be made based on the theory of orthogonal categories by Chi (2013). When a learner encounters a new phenomenon, they will try to understand it. However, they will not be aware if they have all schemas required to correctly understand this observation. If they miss a necessary schema, they are bound to arrive at an incorrect understanding. If this incorrect understanding provides predictions that align with the observed reality "well enough", it might not be noticed as such.

Since an instructor can never know the current understanding of all students in their course, it is practically impossible for them to ensure all students have the understanding necessary to correctly understand all new information presented in class. However, trying to prevent any misconceptions in instruction would not only be futile, but also pointless. Students will inevitably make observations outside of class that cause a misconception. Therefore, misconceptions should not be seen as an error that must be avoided at all cost, but as an inevitable part of learning. A student that holds a misconception has not failed in learning, but simply done one step on their path to a correct understanding.

For this reason, many researchers advocate to not use the term 'misconception'. Instead they suggest more neutral or even positive terms such as 'prescientific conception' or 'alternative conception' (Wandersee et al., 1994; Hammer, 1996). In this thesis the term 'misconception' is used due to its practicality. It can be understood without knowing the precise definition (Wandersee et al., 1994). This decision should not be seen as a strong opinion on that matter by the author. When talking to students, the author tries to avoid framing their statements as 'misconceived'.

2.3.4 *Tutorial Worksheets*

Based on the research on conceptual change presented above, effective teaching materials must not simply present students with correct information, but help them change their conceptual understanding. This change can for example be accomplished by confronting students with possible misconceptions or introducing missing concepts and categories. The so-called *Tutorials* are teaching materials that build on these two approaches.

Tutorials are research-based active learning materials that have been first developed by the Physics Education Group (PEG) at University of Washington (McDermott, 2001). During the last decades, several research groups have developed Tutorials and many more universities have used them in their teaching (see e. g. Sections 3.2 and 3.3).

The design and evaluation of individual Tutorials has been described in several papers (e. g. Loverude et al., 2010; Smith and van Kampen, 2011; Kautz, 2011). The general research-based process for developing a Tutorial as well as some general design principles have also been documented by Shaffer and McDermott (1992). The specific design principles of Tutorials, like the types and phrasing of questions, have so far not been described in literature. The following description of Tutorial design principles is based on an informal analysis of Tutorials as well as the personal experience of the members of the Engineering Education Research Group (EERG)[3].

If the reader is not familiar with Tutorials, it is recommended to not only read the description below but also examine Appendix B, which contains several complete Tutorials. The design of individual Tutorials will be discussed in detail in Chapters 8 and 9.

The usage of Tutorials at TUHH is described in Section 4.3 (p. 57).

Each Tutorial is a worksheet on one specific subject. For many subjects, sets of Tutorials have been published that cover the whole cur-

3 At the time these ideas were formed, the EERG consisted of Christian Kautz, Dion Timmermann, Julie Direnga, Ferdinand Kieckhäfer, Alette Winter, Layla Tulimat, and Nils Gayer. The coordination and compilation of the document was mostly led by Dion Timmermann.

riculum of a typical course. The primary example are the *Tutorials in Introductory Physics* (McDermott and Shaffer, 2012) that cover many different parts of the physics curriculum. They have been translated into Spanish (McDermott and Shaffer, 1997), Korean (McDermott and Shaffer, 2008), German (McDermott and Shaffer, 2009), and Greek (McDermott and Shaffer, 2011). In German, sets of Tutorials for the subjects of Electrical Engineering (Kautz, 2010) and Engineering Mechanics (Kautz et al., 2018) have also been developed and published.

Tutorials can be described by a set of *general properties* that apply to all Tutorials and mostly deal with their use as well as a list of *specific design elements* that apply to the text of a Tutorial. Most Tutorials only use a few of the specific design elements.

2.3.4.1 *General properties of Tutorials*

The following is a list of properties that apply to all Tutorials.

STUDENTS WORK IN SMALL GROUPS Students are strongly encouraged to work on Tutorials in groups of 3–4. While most Tutorial worksheets do not state this explicitly, it is explained in the preface of most, if not all, books containing sets of Tutorials (McDermott and Shaffer, 2002; Kautz, 2010; Kautz et al., 2018). How to encourage students to form groups is an important aspect in the training of teaching assistants (TAs).

Learning in groups has two primary functions in the context of Tutorials. Firstly, the group provides a forum for discussion. Many tasks ask students to explain their reasoning. The student giving an explanation practices to explain their understanding, while the remaining students in the group practice to critically evaluate the other student's understanding. Secondly, groups increase the probability that a student is made aware of all relevant misconceptions. Even though a student might have a misconception, this misconception might not be triggered by a certain task. If a student works with others, it becomes more likely a relevant misconception is expressed by at least one student in the group, allowing it to be addressed.

STUDENTS CONSTRUCT KNOWLEDGE ON THEIR OWN Tutorials are designed so that the relevant concepts that students are supposed to learn are not simply told or presented to them. Instead, students have to construct these concepts themselves. Relationships like Kirchhoff's Laws are not introduced in Tutorials as part of the printed text, but can be observed in experiments or are deduced from previous knowledge. Questions then guide students to generalize their observations or deductions. Only after students have described a law in their own words, it is given a name in the printed text. Arons (1983) named this approach "idea first and name afterwards".

If certain pieces of information have to be introduced, like a notation or a quantity that students might not have used before, these are clearly separated from the main text using boxes or other typographical means. This creates a separation between the main text of the Tutorial, which focuses on student thinking, and the additional information that students are simply given. Such pieces of information, however, are only given when necessary. Tutorials are designed to complement and not replace traditional components of a course like lectures and textbooks. It is expected that students are introduced to relevant concepts in their lecture or textbook (McDermott and Shaffer, 2002).

STUDENTS ARE SUPPORTED BY TEACHING ASSISTANTS Redish (2003) recommends 1 teaching assistant (TA) for every 15 students, Shaffer and McDermott (1992) recommend 20 to 25 students per TA. The EERG at Hamburg University of Technology[4] (TUHH) usually uses groups of 20 students per TA, in a classroom setting with hundreds of students even up to 40 students per TA.

McDermott stresses that "tutorial instructors do not lecture but ask questions designed to help students find their own answers" (McDermott and Shaffer, 2002, p. iii). Koenig et al. (2007) confirmed the importance of this aspect in a study. They found "that students [who worked in groups and were simply told the correct answers by the TA] tended to accept without question the correct answers given by the TA during checkpoints, even when the students' own original answers were incorrect. In most cases the students merely altered their answers on their worksheets without discussing the correct answers among themselves. In contrast, we observed during the study that those students [who worked in groups and were not told the correct answers but engaged in a Socratic dialogue by the TA] engaged in more dialogue with the TA and also among themselves when they learned that their original answers were incorrect. [The Socratic dialogue] not only got the students to question their own understanding of the material but also seemed to generate more discussion among the students and TA." They also "have evidence to suggest that [the Socratic dialogue] was better than the other [teaching style where students were told the correct answer] at moving students away from their initial misconceptions" (Koenig et al., 2007).

STUDENTS ARE NOT PROVIDED SAMPLE SOLUTIONS After a recitation section, students in Germany are often given detailed solutions to the problems they worked on during that section. Consequently, German students often expect to be given sample solutions to Tutorials, especially if not all students were able to complete a Tuto-

4 "Technische Universität Hamburg" in German, formerly "Technische Universität Hamburg-Harburg".

rial during a particular recitation section. However, sample solutions do not exist for Tutorials and TAs are instructed to neither provide nor create them.

As Koenig et al. (2007) showed in the quote above, students who were simply told the correct answer instead of being guided through a Socratic dialogue tended to simply accept a correct answer without questioning their own incorrect understanding. Obviously, sample solutions given to students would result in the same unwanted effect and could even lead to students memorizing sample solutions without understanding the relevant concepts.

Additionally, sample solutions would suggest the possibility to complete Tutorials alone at home. Koenig et al. (2007) warn of this: "Although it may be tempting to use the Tutorial worksheets as individual home activities to save class time or to assign the worksheets to students absent from recitation, the results of our study clearly indicate that this level of implementation of the Tutorials is no more effective than [...] traditional recitation".

Lastly, model solutions can over-emphasize a particular wording of an answer when instead many answers are acceptable.

TUTORIALS SUPPLEMENT TRADITIONAL INSTRUCTION Tutorials are not designed to replace elements of traditional instruction like lectures and recitation sections focused on numerical problems. Instead, they are designed to "be used to supplement the lectures and textbook of a standard [...] course" (McDermott, 2001). Therefore, Tutorials only address parts of the curriculum that are particularly difficult for most students, often not incorporating typical elements of lectures and recitation sections like definitions, algorithms for standard problems, or exercises for students to practice.

2.3.4.2 *Typical Elements of Tutorials*

The general properties of Tutorials presented above and general advice on the design of conceptual tasks result in design elements that can be found in many Tutorials. The most important ones are presented in the following. When designing a Tutorial, these elements can be seen as the building blocks out of which a Tutorial can be constructed. A Tutorial that adheres to the properties described above, can, however, contain none of these elements and still be effective. A Tutorial that includes *all* of the elements listed below will likely be more cluttered than useful.

STUDENTS USE AND COMPARE DIFFERENT REPRESENTATIONS Some Tutorials ask students to draw sketches or to complete existing diagrams, such as free body diagrams, equivalent circuits, phasor diagrams, or color coding. Such graphical elements can fulfill different functions: (1) They form a basis for group discussions. Since diagrams and sketches can make misconceptions visible or simply reduce a problem to its core, they can make it easier to identify and discuss the relevant aspects of a problem. (2) Students get to know and apply graphical tools. Depending on the rest of the course and the tools, these could be previously unknown to the students. (3) Students are given a different (visual) approach to the course content already presented through text and equations. An example that covers all of the three aspects above is the color-coding used in Task 1.1 of the Tutorial *Potential*. It (1) makes different potential values visible, making it easier to discuss the potentials in a circuit, it (2) is usually a representation students have not used before, and it (3) allows students to see the distribution of potentials in a circuit, giving them a new view on voltages in a circuit.

The design of that Tutorial is described in Section 9.6 (p. 233).

STUDENTS PERFORM SIMPLE EXPERIMENTS Many Tutorials contain real-world experiments that students perform while working through the Tutorial. These experiments are usually designed so that they can be set up quickly, requiring only few materials like marbles and a ramp or a battery, bulbs, and cables. In rare cases, more complex experiments are performed as a demonstration or presented as a pre-recorded video.

Experiments can be integrated into a Tutorial in two different ways. On the one hand, they can form the basis for the development of a model, like Task 2.2 in the Tutorial *Current and Resistance*. On the other hand, they can be used to verify students' predictions, like Task 1.9 in the Tutorial *Voltage*. In both cases, the purpose of the experiment is to relate the discussed concept to reality and to use real-world observations instead of the authority of the instructor to verify the correctness of students' results.

The full Tutorial is presented in Appendix B.1 (p. 309).

The full Tutorial is presented in Appendix B.4 (p. 331).

Topics that do not allow for real-world experiments in class, such as the theory of relativity, can employ a gedankenexperiment. While these experiments do not relate students' results to the real-world per se, they still allow students to verify their results based on logic, instead of the instructor's authority.

STUDENTS MAKE PREDICTIONS Before performing an experiment, students are regularly asked to predict its outcome, by e. g. stating if a certain quantity (e. g. the brightness of a bulb) will change. Examples are tasks 2.1 and 2.2 in the Tutorial *Voltage*. TAs should encourage students to write down their predictions. This allows the students and TAs to refer back to the students' predictions after the experiment has been performed. Additionally, students could easily downplay a possible discrepancy between their prediction and the outcome of the experiment as a trivial error or a technicality if the predictions were not written down.

The full Tutorial is presented in Appendix B.4 (p. 331).

STUDENTS WORK ON PRECISELY DEFINED PROBLEMS Most of the tasks in a Tutorial contain a detailed problem setup, like an electric circuit, about which specific statements have to be made (see next element). Such problem setups prevent students from simply reciting concepts by heart ("For every force there is an equally large but opposite force.") and instead require them to apply these concepts to specific situations ("A car crashes frontally into a truck. Compare the force the car exerts on the truck to the force the truck exerts on the car.").

STUDENTS PERFORM SPECIFIC ACTIONS WHEN ANSWERING Tasks in Tutorials always contain prompts that require a specific action, like "describe ..." or "rank ...". They do not contain prompts that ask for general answers like "define ..." or "what is ...". Prompts that require specific actions make the level of detail transparent that is expected in the students' answers. This in turn increases the likelihood that the answers given by different students in a group are similar in their level of detail, making discussions more fruitful. Additionally, such prompts prevent textbook answers, as the prompt forces students to perform a specific action as part of their answer.

STUDENTS EXPLAIN THEIR REASONING A large fraction of the tasks in a Tutorial requires students to answer qualitative questions. Virtually all of these tasks ask students to make their reasoning explicit, resulting in several benefits: (1) Students cannot simply guess an answer, since they also have to come up with an explanation. (2) The explanations can uncover uncertainties and errors on part of the student, since the student's thinking process is externalized. (3) The repeated emphasis on explanations supports the fundamental stance of Tutorials that the world can be explained rationally. When a student is asked to explain their reasoning for a prediction, the explanation helps to specify the assumptions that lead to the student's answer.

STUDENTS REGULARLY DISCUSS THEIR ANSWERS WITH A TA At certain points, Tutorials instruct students to discuss their answers with a TA. Such a statement can for example be seen after Task 1.7 in the Tutorial *Potential*. The intent behind such a prompt is to ensure that even groups of students that would normally not call for a TA will discuss relevant answers with one. These prompts are usually placed after critical tasks where students are supposed to notice a conflict in their reasoning or where a certain answer is required for upcoming tasks.

The full Tutorial is presented in Appendix B.8 (p. 361).

STUDENTS ASSESS STATEMENTS OF FICTITIOUS STUDENTS Although they cannot be found in any of the Tutorials discussed in this thesis, Tutorials often use statements of fictitious students. In many cases, these statements take the form of a discussion between several students. They usually contain typical misconceptions or errors in reasoning. To highlight that these statements are not part of the main text of the Tutorial and could be incorrect, the statements of the fictitious students are usually set in a different font that imitates handwriting. Students are usually asked to assess the correctness of the fictitious statements or decide which fictitious answer they agree with. Sometimes it is explicitly stated that some or all of the statements are incorrect and students are only asked to identify the errors.

The statements by fictitious students are designed to ensure that certain misconceptions are made explicit and consequently discussed in the Tutorial. This type of task also allows students to practice the critical evaluation of statements and identification of logical errors.

STUDENTS WORK THROUGH STRUCTURAL ARCS Many Tutorials contain several tasks that together follow what could be called a structural arc. Two of these arcs are described in the following:

Observe – Recognize – Apply. A first task asks students to *observe* a phenomenon. With this task, they are meant to *recognize* a principle or concept. To help students overcome a possible misconception about the respective principle, further tasks ask them to *apply* their new conception (McDermott, 1991). An example for this arc is the introduction of current flow at junctions in Section 3 of the revised version of the Tutorial *Current and Resistance*. In the circuit they build up, students are meant to *observe* that bulb 1 glows brighter than bulbs 2 and 3, while bulbs 2 and 3 are equally bright. Based on this observation, students are meant to *recognize* that the current through bulb 1 actually splits at the junction, and half of it flows through bulb 2, the other half through bulb 3. This concept of current splitting at junctions is then *applied* throughout the rest of the Tutorial as well as the subsequent Tutorial *Voltage*.

The full Tutorial is presented in Appendix B.2 (p. 319).

The full Tutorial is presented in Appendix B.4 (p. 331).

Elicit – Confront – Resolve. First, a task or pre-test is used to *elicit* students' (mis)conceptions. Then, a second task is used to *confront* students with their misconception. This confrontation can, for example, be achieved by discussing a similar or identical problem as in the first task or pre-test. Further tasks and possibly discussions with the TA are used to *resolve* the student's issue by helping them to reach the correct understanding (McDermott, 2001). An example for such a structural arc is the Tutorial *Potential*. The Tutorial uses its integrated pre-test (Task 0.1) to *elicit* students' misconceptions about the voltage across the open switch (V_{BC}). Then, the electric potential is introduced (Section 1) and used to analyze the circuit from the pre-test (Section 2). Task 2.6 *confronts* students with their likely incorrect pre-test answer. Further tasks on the electric potential and discussions with the TA are used to *resolve* any remaining conflicts.

The full Tutorial is presented in Appendix B.8 (p. 361).

INTRODUCTORY PARAGRAPH Most of the Tutorials developed by the EERG at TUHH (see Kautz, 2010; Kautz et al., 2018) start with an introductory paragraph that describes the idea behind or goal of the Tutorial. Sometimes, this paragraph also describes the general approach used in the Tutorial, as can for example be seen in the Tutorial *Current and Resistance*. These paragraphs are intended to give an overview of the Tutorial and activate prior knowledge. They are also used to highlight the similarity of or difference between Tutorials, when for example Tutorials build upon each other, as in the Tutorial *Voltage*, or a Tutorial uses a simplification that is removed in a later Tutorial. In the Tutorials developed by the PEG, such paragraphs are extremely rare.

The full Tutorial is presented in Appendix B.2 (p. 319).

The full Tutorial is presented in Appendix B.4 (p. 331).

SUMMARY BOXES OR PARAGRAPHS After a concept has been developed or analyzed by students, its relevant aspects are sometimes summarized. This summary is usually typographically differentiated from the main text. The Tutorials shown in Appendix B use boxes for this purpose, the original Tutorials by the PEG use text with an increased line spacing. As described above (see p. 27), Tutorials usually let students discover or develop a concept before naming it. This naming is commonly done in such a paragraph. An example for such a box can be found at the top of page 4 of the revised version of the Tutorial *Current and Resistance*. It states that the "behavior of the electric current [students had investigated] is referred to as Kirchhoff's Current Law." When possible, such boxes and paragraphs are placed after a page break to prevent students from accidentally reading the summary before completing the tasks it summarizes.

The full Tutorial is presented in Appendix B.2 (p. 319).

PRE-TESTS, POST-TESTS, AND HOMEWORK According to McDermott and Shaffer (2002), "Tutorials comprise an integrated system of pretest, worksheets, homework assignments, and post-tests" (p. iii).

While the EERG at TUHH relies on pre- and post-tests for the development of Tutorials, instructors at TUHH rarely use such tests when not required for research on student understanding. Homework assignments have been published as part of the German translation of the *Tutorials in Introductory Physics* (McDermott and Shaffer, 2009) as well as the German *Tutorials in Electrical Engineering* (Kautz, 2010). However, due to the infrequent usage of these homework assignments, the recently published German *Tutorials in Engineering Mechanics* (Kautz et al., 2018) so far do not have an accompanying set of homework assignments.

2.3.5 *Other Active Learning Methods*

While this thesis exclusively discusses Tutorials as a method for active learning, there is a multitude of other active learning methods.

Examples include peer instruction (Mazur, 1997), inquiry-based learning activities (Adam et al., 2015), flipped classroom instruction (Willey and Gardner, 2013), and problem-based learning (Perrenet et al., 2000). It is likely that the results from this thesis can be used to create learning materials that use any of these methods. If used appropriately, these methods are in the author's opinion likely to achieve similar results in student learning.

Tutorials, however, are particularly suitable for research on student understanding. As the worksheets themselves are printed pieces of paper, researchers and instructors know word by word, which information and tasks students are given. This is not true for several of the other active learning methods named above, which rely more heavily on the oral presentation of an instructor. Certainly, not every student will have the same experience when working through a Tutorial, as TAs spontaneously react to student questions and discussions between students vary from group to group. These differences, however, can be seen as disturbances that Tutorials must be robust against. A Tutorial that has been tested empirically will likely be similarly effective at many other institutions when used properly.

2.4 DECODING THE DISCIPLINES

Tacit knowledge is also discussed in Section 10.1.2 (p. 275).

In contrast to the student-focused conceptual change framework, Decoding the Disciplines (DtD), which was first described by Pace and Middendorf (2004), is an instructor-focused process for the iterative improvement of teaching. Each iteration identifies one task that students in the instructor's course struggle with. It is then analyzed how the instructor solves this task, revealing their tacit knowledge, i. e. the knowledge that they possess and use while solving the task, but are not aware of and thus do not make explicit without being prompted to do so. This knowledge is then made explicit to students through an intervention, which is incorporated into the instructor's course.

In their description of DtD, Middendorf and Pace (2004) discuss *tasks* that students fail to complete successfully and *skills* that they need to learn and demonstrate. However, DtD is less interested in tasks and skills that only require simple procedural knowledge but instead focuses on students' ability to *analyze*, *evaluate*, and *synthesize*, i. e. the most demanding tasks on Bloom's (revised) taxonomy (Anderson et al., 2000). Middendorf and Pace (2004) describe these as tasks that require an expert's *way of thinking*.

As described by Middendorf and Pace (2004) as well as Middendorf and Shopkow (2017), Decoding the Disciplines focuses on the *thinking* required to complete certain *tasks*, but does not discuss students' *understanding of concepts*. Middendorf and Shopkow (2017) claim that "The goal, [of decoding] is not to understand the *content* of a lesson or a course – something experts can easily explain – or how to teach it

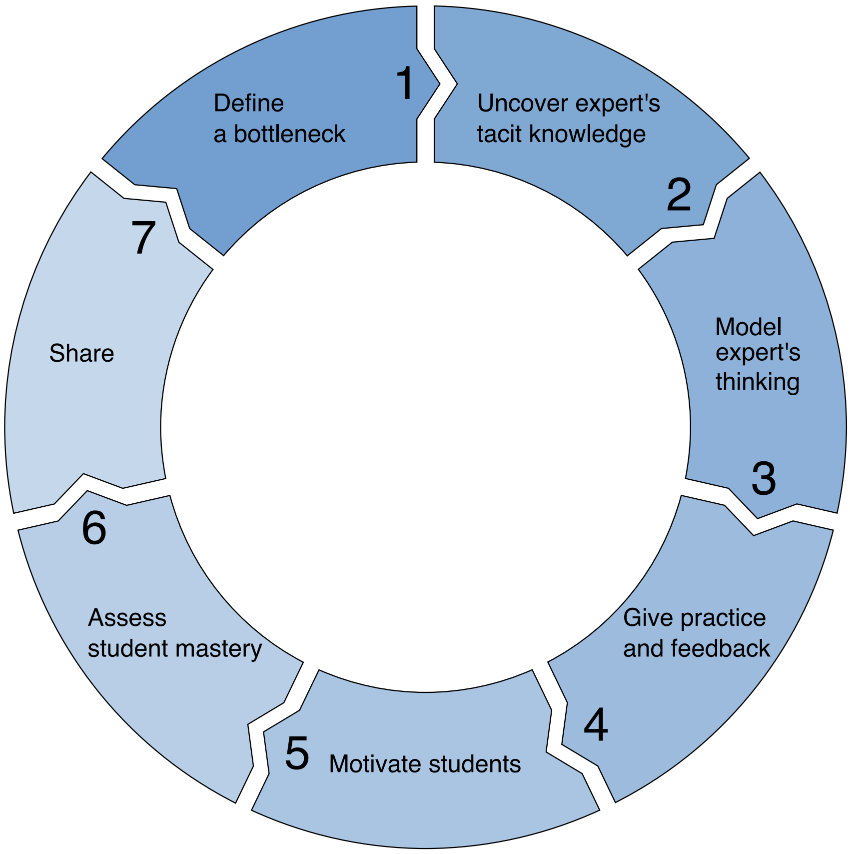


Figure 2.4: The “Decoding the Disciplines Wheel”, identifying the seven steps in the decoding process. Figure adopted from Middendorf and Shopkow (2017).

[...] but instead to grasp the *mental processes* faculty rely on to operate within their field. These mental processes are often more complex for experts to explain because, for them, mental processes are tacit knowledge and may never have been explicit.”[5] It certainly is true that in many cases, there is no need to decode an expert’s understanding of a certain *concept*. However, as this thesis will show, there are cases where tacit knowledge is crucial to the understanding of a concept. Consequently, the description of DtD in the following is extended to the understanding of concepts. This extension, however, should not be understood as a major change to the theory of DtD.

2.4.1 *The Seven Steps in Decoding a Discipline*

Each iteration of the DtD process consists of seven steps, usually represented as segments of a circle, as in Figure 2.4. Based on Middendorf and Pace (2004), these steps are described below:

The process always starts with the instructor (1) DEFINING A BOTTLENECK, a point in instruction where students get stuck. Defining

5 emphasis by original author

the bottleneck also includes to explicitly identify the skill, task, or concept that is troublesome for most students in the course.

For the previously defined bottleneck, the instructor then needs to (2) UNCOVER AN EXPERT'S TACIT KNOWLEDGE, their *way of thinking* that allows them to successfully perform the skill or task or use the concept students fail at. The expert in many cases is the instructor themself. This step requires a careful analysis of the expert's approach or understanding to reveal tacit knowledge or ways of thinking that they might employ without realizing. DtD suggests several different approaches, depending on the resources available. These range from reflective writing and mind maps (Middendorf and Shopkow, 2017, p. 36) to the decoding interviews described in the following section.

Once it is understood how the expert performs the skill or task or understands the concept that the students fail at, the expert's thinking is made explicit to the students. The instructor has to (3) MODEL THE EXPERT'S THINKING. This modeling can for example be realized by detailing the thinking process of an expert when solving an exemplary task or by describing how an expert visualizes a problem or concept. Zolan et al. (2004) provide a good example of such a modeling task. Middendorf and Pace (2004) note that steps 2 and 3 are most demanding in a DtD cycle. While the expert likely considers many different aspects when solving a task and has quite a complex understanding of relevant concepts, the instructor has to select which aspects of the expert's thinking or understanding to model for the student. A model with too many aspects would likely overwhelm students and exceed the time available in the course. At the same time, the instructor has to provide enough redundancy and variety in the modeling in order to accommodate different students with different backgrounds and ways of thinking.

Once the expert's thinking or understanding has been made explicit to students, the students must be given the opportunity to (4) PRACTICE AND GET FEEDBACK. In the context of tasks or skills, this could be implemented as a series of exercises that require the students to use an increasing number of aspects of the model presented. In the context of understanding a concept, it could be implemented in a series of problems that require students to apply the concept in different ways, allowing them to test their new understanding in various situations. Middendorf and Pace (2004) suggest the use of active learning techniques, such as the ones discussed in Section 2.3.5.

Besides the importance of practice, DtD also stresses the role of the instructor to (5) MOTIVATE STUDENTS. This is especially important if the tasks used for practice do not have an obvious relation to students' goals or the rest of the course. Middendorf and Shopkow (2017) also discuss bottlenecks which require students to change their beliefs and values or accept unpleasant knowledge. While such examples are rare in the sciences, they can be crucial in students' development in the social sciences and humanities.

Following the ideas of SoTL, DtD stresses the importance of a scientific approach to the improvement of teaching. Therefore, instructors are encouraged to (6) ASSESS STUDENT MASTERY before and after students go through steps 3 to 5. The pre-test allows them to adapt their teaching to students' requirements. The combination of the pre- and post-test allows them to assess the effectiveness of the intervention and determine if further changes are required. Middendorf and Pace (2004) advertise diverse methods for testing, similar to the conceptual questions discussed in Chapter 5.

Middendorf and Pace (2004) also emphasize the importance to (7) SHARE one's insights with the educational community, which is also an important part of SoTL.

2.4.2 *The Decoding Interview*

The best known method for step 2 of the decoding process is the decoding interview. In such an interview, the interviewer simply asks an expert (often the instructor) to explain how they would solve the task or understand the concept that presents the bottleneck to students. As Middendorf and Pace (2004) observe, the initial explanation of an expert often makes logical leaps and contains unexplained terms and undefined processes "that seemed too obvious to be consciously recalled" (p. 6). The interviewer then asks the expert to explain these unexplained terms and undefined processes and to specify the skipped steps and assumptions. Each explanation can require the interviewer to request additional clarifications. The interviews often result in an "Aha!" moment, where the expert (or instructor) notices a way of thinking or relation that was crucial to their understanding but that they never had explained to students.

The role of the interviewer is critical to the success of the interview. They must recognize every piece of tacit knowledge the expert uses and notice all steps and assumptions the expert skipped. They then have to decide which statements by the expert can be expected to be understood by a student and which need to be clarified.

Asking for too many clarifications and details can annoy the expert and thus put a strain on the interview situation. Asking too few questions could result in missing the relevant question and the expert never revealing their tacit knowledge. It is ideal if the interviewer themself is an expert in a field related to the one the interview is about. They would then have a good basis for understanding the reasoning used in the subject in question, without having any tacit knowledge about the expert's subject (Middendorf and Shopkow, 2017). The interview ends once the expert has fully described their understanding of the concept and the interviewer has no open questions.

2.4.3 *Comparison of Decoding the Disciplines with other Frameworks*

Both, DtD and the idea of misconceptions in conceptual change research, are frameworks that investigate discipline specific knowledge and understanding. DtD focuses on the instructor's "hidden" knowledge that was previously not taught to students, but will improve their learning. In contrast, misconceptions research identifies students' incorrect knowledge that hinders their learning and identifies ways to help them overcome their incorrect conceptions. APOS-Theory, a third framework introduced in Section 2.5, investigates the structure of the knowledge itself.

DtD follows the tradition of SoTL in that it asks instructors, who often primarily see themselves as researchers, to look at their own teaching from a scientific perspective. It guides them to analyze their own teaching and to systematically develop and test ways to improve it, which they then publish to disseminate this new knowledge. Thus, DtD is also a method for the professional development of instructors. In contrast, misconceptions research is primarily performed by professional educational researchers, who also publish their results to provide resources for instructors.

Many of the methods used to assess student learning in DtD are also used in misconceptions research. Besides such methods to asses student learning, instructors also have to select methods for teaching. Pace and Middendorf (2004) see DtD as a tool to structure this selection process. Using DtD, instructors can identify the methods that their students need most.

DtD, especially the idea of a bottleneck, intersects with the idea of threshold concepts, which will be introduced and discussed in Chapter 10. Both theories use similar language, proposing that students can get "stuck" while learning and need to overcome a "threshold".

2.4.4 *How Decoding the Disciplines is Used in this Thesis*

Although developed independently, there are similarities between the seven steps of the DtD cycle (see Figure 2.4) and the development and use of Tutorials. The development of a Tutorial is often triggered by the discovery of one or more misconceptions that cause students to incorrectly answer certain conceptual questions (step 1). Researchers then need to describe the correct understanding students are supposed to gain (step 2). However, this step rarely needs to be done explicitly. Afterwards, the Tutorial is designed so that students working through it will make the required connections (step 3). The Tutorial also contains tasks that allow students to apply and test, i. e. practice (step 4), their new understanding. Giving feedback (step 4) and motivating students (step 5) are the core responsibilities of the TAs that support students while working on a Tutorial. A new Tutorial is evaluated using pre- and post-testing (step 6) and once finished, it is published (step 7) to be used by instructors world wide.

While the full 7-step DtD cycle is not used in this thesis, some ideas from DtD, especially step 2, are used in different parts of it. In Chapter 8, Tutorials are analyzed using a method that is very similar to a decoding interview. In Chapter 9, the complexity of circuit analysis using current and voltage is compared to the complexity using current and the electric potential. To allow for an objective comparison, most of an electrical engineer's familiarity with circuit analysis is removed by presenting it in a mathematical notation. This approach presents a different method to step 2 in the DtD cycle. Both approaches are discussed in more detail in the respective chapters.

2.5 APOS-THEORY

The previous two sections described different approaches to EER that focused on students' and instructors' conceptions of subject matter. An alternative approach is to investigate the logical relations between the different concepts in a subject directly. This kind of approach is effectively taken every time a textbook author considers the order of topics in a book they are planing to write. APOS-Theory, introduced in the following, is a unique representation of this content-focused approach. It is more objective than the two approaches presented in the previous sections, in that it does not ask how a human *understands* the relevant subject matter, but what the structure of the subject matter itself *is*.

APOS-Theory was developed for and is almost exclusively used in mathematics education. The abbreviation APOS stands for the four key components of the theory: *action*, *process*, *object*, and *schema*. Based on this theory, every mathematical concept can be understood on three different levels[6]: as an action, a process, and an object. In the following section, these three understandings and their relation will be discussed using the standard example in APOS-Theory: the understanding of a function. Schemas will be discussed afterwards. The descriptions in the following are based upon personal communication with Ed Dubinsky, the founder of APOS-Theory and, where noted, publications by Breidenbach et al. (1992), Asiala et al. (1997), and Arnon et al. (2013).

6 These 'levels' are called *conceptions* in APOS literature. To avoid confusion with the term 'concept', as used in conceptual change theory, misconceptions research, and DtD, the term 'level' is used instead in this thesis.

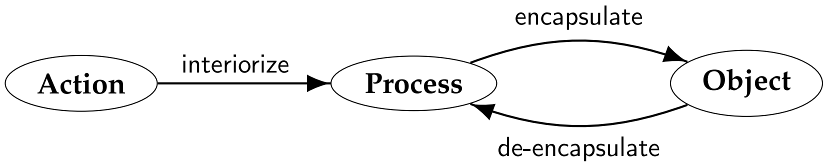


Figure 2.5: Relation between *Action*, *Process*, and *Object* in APOS-Theory.

2.5.1 *Action, Process, and Object*

The relations between action, process, and object are illustrated in Figure 2.5 and excellently explained by Breidenbach et al. (1992): "An *action* is any repeatable physical or mental manipulation that transforms objects (e. g., numbers, geometric figures, sets) to obtain objects. When the total action can take place entirely in the mind of the subject, or just be imagined as taking place, without necessarily running through all of the specific steps, we say that the action has been *interiorized* to become a *process*. It is then possible for the subject to use the process to obtain new processes, for example by reversing it or coordinating it with other processes. [...] Finally, when it becomes possible for a process to be transformed by some action, then we say that it has been *encapsulated* to become an *object*." When required, an object can be *de-encapsulated*, i. e. the process which has been encapsulated can be extracted, and thus used (Breidenbach et al., 1992).

In other words: Any mathematical concept, like a function, can be understood as an action, as a process, or as an object. To reach an action-level understanding of a concept, the action associated with the concept simply has to be performed. To reach a process-level understanding of any concept, there are three different approaches. A learner can (1) perform the associated action often enough, possibly with varying inputs and in varying situations, so that they *interiorize* that action. A learner can also (2) directly manipulate a process to form a new process, for example by inverting a process to form its inversion. They can also (3) combine multiple processes, by for example applying a process to the result of another process. This combination of two processes would be another process. To reach an object-level understanding, there again is only one way (Breidenbach et al., 1992): By performing actions or processes on another process, that process can be encapsulated into an object.

It might seem that inverting a process or coordinating two processes to form new processes were actions applied to objects, i. e. that forming new precesses from existing ones required the existing ones to first be encapsulated into an object. However, that is not necessarily the case (see e. g. Arnon et al., 2013, pp. 23-25). According to APOS-Theory, a learner who e. g. inverts a process might think about a process as an "automatic action" and reverse the direction of that action in their mind. A learner with a process conception of a function might for example think of a function as a process that maps elements from one set to another. They might then invert the direction of this mapping without thinking about the process as a whole. In that case, they have not treated the process as an object. Thus, forming new processes by manipulating existing processes does not necessarily require an object level understanding of the processes that are manipulated.

In APOS literature, an action-level understanding is described as *external*. The learner is able to correctly perform the steps that are part of this operation, but they do not have a cohesive understanding of the operation. A learner with an action-level understanding of functions is, for example, able to calculate the value $f(x)$ of that function. When given the function $f(x)=x^2$ and the argument $x=2$ and asked to determine the value $f(x)$, the learner would simply replace every x in $f(x)$ with 2 and calculate the result. They would, however, not be able to answer the question of whether the function f could return negative values. They might try to calculate the value of the function for a few arguments, but would not be able to make a generalized statement with a sound argument. While the reason for their lack of answer might be that they have not yet understood how to carry out such a proof, the main obstruction would be that they only understand a function as an operating procedure. They have only understood that they must replace x with the argument they were given and calculate the result.

With a process-level understanding of a mathematical operation, a learner is able to think about the operation without actually performing it. The previously external action is now an *internal* process. Using the example of a function, the learner is now able to think about the whole function $f(x)$ and in the case of $f(x)=x^2$, for example, able to draw the function and determine that there can be no negative value returned. A learner that has gained a process-level understanding can also invert a process, e. g. understand an inverse function, or link two or more processes to form a composition, e. g. understand the composite function $f(g(x))$. In many cases, a process-level understanding of a particular operation might be the highest level of understanding required of a student.

By performing operations on a process, a learner can encapsulate that process into an object. They can now use or manipulate that object with other operations or processes. While the process-level understanding basically replaces the action-level understanding, the process and object co-exist. When required, the object can be de-encapsulated to be used as a process. A learner who has reached an object-level understanding of an operation can use the operation as a process or as an object, whichever is required at the moment. The object-level understanding of a function is, for example, necessary for understanding derivatives, which are operations applied to functions,

i. e. processes applied to objects. A learner with an object understanding of a function, however, is still able to think about functions in the form of a process.

2.5.2 *Schemas*

Multiple processes and objects can be organized to form a schema. A schema itself can again be treated as an object and then incorporated into another "higher level" schema (Asiala et al., 1997). Consequently, schemas present another level of abstraction that can be used to describe how different operations and objects can be grouped together and treated as a whole. While schemas are a corner stone of APOS-Theory, being part of the name after all, they are a less developed part of the theory (Asiala et al., 1997). They are not used in this thesis.

2.5.3 *Genetic Decomposition*

As described in Section 2.5.1, a process-level understanding can only be reached through the repetition of an action or the manipulation or combination of other processes. An object-level understanding can only be reached by performing an action or process on another process. Actions and processes, in turn, are performed on something, i. e. an object. Consequently, to reach an action, process, or object-level understanding of any concept, the action, process, or object-level understanding of at least one and in many cases two or more other concepts is required.

For any given concept and level of understanding, a so-called *genetic decomposition* can be created. A genetic decomposition of a concept is a description of all the actions, processes and objects that a learner must have learned in oder to be able to learn that concept on a certain level. The genetic decompositions for the different levels of understanding of a concept will be different. In practice, the decomposition deconstructs a concept into concepts that students in a given course are supposed to know. In the author's opinion, for any concept in mathematics, the decomposition could be extended until the basic axioms of mathematics are reached. Is is unclear if the same is true for concepts in the realm of physics.

Instruction based on APOS-Theory helps students reach a certain level of understanding of a concept by going through all of the steps of the genetic decomposition. While such instruction might seem slow, as many dependent concepts have to be introduced that in other courses are not introduced explicitly, students who are taught with this approach will have all the knowledge they require to proceed at every step. Consequently, according to Ed Dubinsky[7], such courses progress faster in the long term than traditionally taught courses.

7 personal communication

3 PRIOR RESEARCH

This chapter provides an overview of relevant research that preceded this thesis. The publications described here either form the metaphorical shoulders this work stands on or can be used to supplement and contrast it.

3.1 STUDENT UNDERSTANDING OF ELECTRICAL ENGINEERING

In the author's opinion, the prior research on student understanding of electrical engineering can be divided into three phases described in the following.

3.1.1 *1970s and 1980s: Early Works*

While research on student understanding of electrical engineering mostly started at the turn of the century, research on student understanding of concepts that are part of electrical engineering started in the late 1970s as part of physics education research (see e. g. Evans, 1978).

A good overview of the early works on student understanding and the teaching of electricity is provided by the proceedings of the international workshop *Aspects of Understanding Electricity* (Duit et al., 1985). Many researchers that were active in the field at that time period participated in the workshop. In the proceedings, McDermott and van Zee (1985) for example reported on a series of 23 interviews that used a circuit layout later described as the five-bulbs test. They discussed student difficulties with parallel and series circuits and described instructional materials that would later turn into *Tutorials*. Von Rhöneck and Volker (1985) reported on students' descriptions of circuits, after having investigated students' conceptions of voltage in earlier research.

Section 7.1 (p. 106) provides details on the five-bulbs test.

Many of the issues reported in *Aspects of Understanding Electricity*, were also described in more detail in journal articles published separately. Cohen et al. (1983), for example reported on a questionnaire to test students' understanding of simple electric circuit concepts. This questionnaire consisted of 4 free-response questions and 10 multiple choice questions that were in many ways similar to a concept inventory. They analyzed the answers given by 145 high school to college-level students and 21 teachers and identified common difficulties. Among other things, they noted that many of the students knew Ohm's Law and were able to correctly apply the equation $V = R \cdot I$ in simple situations, but failed to do so in more complex scenarios. They also reported that about a third of their students believed a battery to behave as an ideal current source.

In 1984, Johsua, who later also participated in the workshop *Aspects of Understanding Electricity*, investigated students' ability to read circuit diagrams. In interviews, he showed students four circuit diagrams. In each diagram, the two points A and B were connected by a wire. This wire was part of a simple circuit consisting of a battery and a resistor. The four circuit diagrams differed in what was additionally connected between the two points. One circuit had a resistor connected in parallel to the wire between A and B, another one had a wire loop connected at one point to the wire between A and B, etc. In all four cases, there was zero voltage between A and B. Johsua found that students' ability to correctly describe current and voltage in the circuit depended on its configuration. Students rarely used the electric potential or voltage but instead focused on the circuit's topological features. They interpreted electrically identical circuits differently, depending on how they were drawn. Students also assumed that all circuit elements that were part of a circuit must have a function.

Being the first on the subject, many of the early publications were not based on prior research. While many publications highlighted specific difficulties of students (like Johsua, 1984), some took a broader approach (like Cohen et al., 1983). As most researchers were from the fields of physics and secondary education research, most of the test subjects either participated in university-level physics courses or were students from secondary school. Engineering students were tested rarely, if at all.

3.1.2 *1990s: Second Phase*

Many publications published in the 1990s can be seen as part of a "second phase" of research on student understanding of electricity. Several publications build upon and refined earlier works.

In part one of their two-part publication *Research as a guide for curriculum development: An example from introductory electricity* (McDermott and Shaffer, 1992; Shaffer and McDermott, 1992), McDermott and Shaffer summarized many observations on students' understanding of electricity. They presented a long list of difficulties and incorrect beliefs that students were found to frequently hold even after traditional instruction. This list includes the "failure to understand and apply the concept of a complete circuit", the "belief that direction of current and order of elements matter", the "belief that current is 'used up' in a circuit", the "belief that the battery is a constant current source" and thus the "failure to recognize that an ideal battery maintains a constant potential difference between its terminals". Also the "failure to distinguish between potential and potential difference", as well as "difficulty in identifying series and parallel connections". For each student difficulty, McDermott and Shaffer present examples from their conceptual tests and interviews. Some of these difficulties had already been reported on by McDermott and van Zee (1985). The second part of their publication presented Tutorials, their approach to address the students' difficulties. These Tutorials are derived in part from the instructional strategies described in McDermott and van Zee (1985).

Engelhardt (1997) presented the DIRECT, a concept inventory testing students' understanding of simple DC circuits. Although it is based on many sources and was developed with the support of a panel of experts, the DIRECT can be seen as a continuation of the work by Cohen et al. (1983). While there are other concept inventories on electrical engineering (for an overview, see Sangam and Jesiek, 2010), the DIRECT is likely used most often. Several of its questions are discussed in this thesis. The DIRECT consists of 29 multiple-choice questions. Since version 1.1, each question has 5 answering options. The test measures 11 concepts, covering the subjects "physics aspects of DC electric circuits", like students' ability to "interpret pictures and diagrams of a variety of circuits", as well as the subjects "energy", "current", and "voltage". As reported later (Engelhardt and Beichner, 2004), the test's reliability has been confirmed using a statistical analysis of the answers from 454/251 high school and 681/441 university students for version 1.0/1.1 of the test. The test has also been validated through a panel of experts and through a factor analysis of the responses as well as individual follow-up interviews for selected questions.

The DIRECT is used in Sections 7.4 (p. 133) and 7.6 (p. 159).

While many studies from this phase are still very relevant today, most of the test subjects were either students in physics courses or students from secondary schools. Similarly, the subject matter investigated was mostly limited to the physics curriculum.

3.1.3 *2000s and Later: Recent Works*

Studies in the 2000s and 2010s focused not only on students in physics courses, but also engineering courses (e. g. Bernhard and Carstensen, 2002). Research shifted to also cover concepts that are taught later in the curriculum or are exclusive to electrical engineering.

In her dissertation, Carstensen (2013) developed a model that describes students' connections between different concepts. She demonstrated this model by investigating engineering students' learning of the Fourier transform in a laboratory setting. Coppens (2016) investigated students' understanding of first order RC filters and their behavior while analyzing a black box containing such a filter in a laboratory setting. Van De Bogart (2017) investigated student understanding of operational amplifiers and designed a Tutorial on this topic.

Still, new research on student understanding of the fundamentals of electricity was published. In 2004, Engelhardt et al. challenged previous research on students' understanding of bulbs and the concept of a complete circuit. Previous research (McDermott and Shaffer, 1992) observed that many students were not able to light a bulb using only a battery, a bulb, and a single wire. Failure to do so was interpreted as students not having understood the concept of a complete circuit, i. e. that there must be a closed conducting path passing through both the source (battery) and load (bulb). Engelhardt et al. showed that half of their students believed that both ends of the filament inside the bulb were connected to the bottom terminal of the bulb. Thus, connecting wires only to the bottom terminal of a bulb could be considered as a student's best attempt to form a complete circuit. In 2013, Stetzer et al. published a paper opposing the conclusion of Engelhardt et al. They reported that pre instruction, only half of their students correctly indicated the internal wiring of a bulb, while post instruction 95% of students had "an adequate knowledge of the internal structure of a light bulb". Still, "only between one-half and two-thirds demonstrated a sufficiently robust understanding of a complete circuit by giving a correct response on a related question involving two batteries". They conclude that "failure to connect a battery, bulb, and wire(s) correctly cannot simply be ascribed to a lack of familiarity with the internal structure of the bulb".

As indicated above, research has shifted since the 2000s to a dedicated investigation of engineering students' understanding of electrical engineering. This thesis is part of that shift. At the same time, it revisits many aspects of previous research and compares the understanding of German electrical engineering students to the previous findings about students in physics courses in other countries.

3.2 TUTORIAL DEVELOPMENT

In addition to research on student understanding, the development and evaluation of instructional materials is also an important part of engineering education research. As this thesis focuses on electrical engineering education research and Tutorials as instructional materials, the following overview presents the three relevant publications on the development and evaluation of Tutorials for the subject of electric circuits.

In part two of their two-part publication *Research as a guide for curriculum development: An example from introductory electricity* (McDermott and Shaffer, 1992; Shaffer and McDermott, 1992), Shaffer and McDermott describe the development of the Tutorials on DC circuits based on their research on student understanding. They detail many of the design decisions made during the development of the Tutorials and assess the effectiveness of the materials. The Tutorials described by Shaffer and McDermott (1992) were later published as part of the *Tutorials in Introductory Physics* (McDermott and Shaffer, 1998, 2012) and translated into several languages (McDermott and Shaffer, 1997, 2008, 2009, 2011).

Kautz further extended the curriculum of the *Tutorials in Introductory Physics* by designing a set of Tutorials on electrical engineering, the German *Tutorien zur Elektrotechnik* (Kautz, 2010). He reported on the development in a publication (Kautz, 2011), focusing on a newly discovered common misconception of phase relationships in AC circuits: Students frequently believed inductors and capacitors had a 90° phase shift between the current through or voltage across them and the current through or voltage across the source. Thus, in a parallel RC circuit connected to a voltage source, they believed there to be a phase shift between the voltage across the battery and the voltage across the capacitor, while in fact both elements are connected in parallel and thus have no phase shift. Kautz (2010) reports that students who participated in the newly developed Tutorial on AC phases performed significantly better than those that only participated in traditional instruction.

The *Physics Education Group* at CASTeL at *Dublin City University* developed a set of instructional materials based on the *Physics by Inquiry* curriculum, a curriculum where qualitative group activities completely replace lectures. As the name suggests, the *Physics by Inquiry* curriculum uses inquiry-based instruction where students perform experiments and afterwards formulate laws of nature they subsequently test. In a publication, Smith and van Kampen (2011) reported on the development of parts of this curriculum focusing on multiple batteries. Using pre-tests, they "found that most students were unable to explain the effects of adding batteries in single and multiple loops, as they tended to use reasoning based on current and resistance where reasoning based on voltage is a necessity". The newly developed curriculum first introduced students to the concept of electric potential. Using the electric potential it then allowed students to "systematically discover rules for how circuits with multiple batteries in multiple loops can be modeled". While students who worked with these materials still showed difficulty to apply their understanding to a new context, their answers "revealed an increased understanding of the roles current, voltage, and resistance play in their model for electric circuits".

This thesis evaluates the effectiveness of two of the Tutorials presented by Shaffer and McDermott (1992), as well as the modifications and additions made by Kautz (2010). The newly developed Tutorial on the electric potential (see Chapter 9) has similarities to the curriculum developed by Smith and van Kampen (2011).

3.3 EFFECTIVENESS OF TUTORIALS

The publications discussed in the previous section not only described the development of Tutorials but also included an evaluation of their effectiveness using pre- and post-tests. Such evaluations, however, are usually very narrow in scope, only considering concepts explicitly addressed in the newly developed Tutorial. In addition, there are also publications that investigate the effect of a set of Tutorials. These usually employ longitudinal studies and standardized tests. Relevant articles are summarized below.

Benegas and Flores (2014) used the DIRECT by Engelhardt to measure high school students' conceptual learning of simple resistive electric circuits. In their longitudinal study, they compared students who were taught traditionally to ones who were taught using the two Tutorials *Current and Resistance* as well as *Voltage*[1] from the Spanish translation of the *Tutorials in Introductory Physics* (McDermott and Shaffer, 1997). Benegas and Flores (2014) note that their students' pretest score was slightly below the 20% random response level of the DIRECT and students in general had "poor communication and reasoning abilities". As a consequence, "each tutorial demanded much longer than the 50 minutes of class time reported at the development and replication sites [...]. This obstacle also appeared in different implementations at the introductory level in local universities [...], where each Tutorial worksheet demanded between 2 and 2½ hours to complete." Still, working with the Tutorials seemed to be satisfying for students, which were eager to perform the experiments included in the Tutorials and participate in the peer discussions. While teacher preparation for the Tutorials was difficult, Benegas and Flores (2014) view the "ready-to-use" nature of the Tutorials as a positive from the teachers' point of view. Their pre- and post-test analysis revealed that students who worked with the Tutorials performed significantly better than the control group, even when both groups had the same instructor. Students of inexperienced instructors who used Tutorials performed almost as well as those of veteran instructors.

Riegler et al. (2016) reported a different experience. They tested the use of Tutorials at a German university of applied sciences for one semester. Before instruction, their students performed quite well in the DIRECT (56% average), albeit with a large spread in performance. Conceptual difficulties seemed to be less common and subtle among their students, compared to what other researchers have reported. In a course that was offered in addition to the traditionally taught courses, students were given a large number of Tutorials on electrical engineering. Riegler et al. report that in the first Tutorials, which slowly introduce the concepts of current, resistance, and voltage, "students felt that they were not allowed to apply the con-

1 The Tutorial *Voltage* was called *Potential Difference* by Benegas and Flores (2014).

cepts and terminology they already knew". The structure of the Tutorials (elicit, confront, resolve) to them was transparent and tedious and the frequent tasks asking students to describe a circuit or explain their reasoning was "perceived as mere busywork and thus resented". At the end of the course, when the Tutorials addressed concepts that the students had no or incorrect knowledge of, students' attitudes changed. Now, students were unsure of their answers and demanded clarification from teaching staff. Riegler et al. observed the "strong perception that the final, 'real' physics is in the formal definitions, and that *Tutorials* are holding the students back." The teaching staff was also not happy with the Tutorials. They lamented the "taxing tutoring conversations" as well as the organizational effort required. Riegler et al. (2016) concluded that the Tutorials could have helped students overcome conceptual difficulties, but that the strong scaffolding of the Tutorials paired with students' high level of knowledge on the subject was not a good match. Possibly aggravated by the low buy-in of teaching staff, students did not take advantage of the learning opportunity. Still, Riegler et al. (2016) claim that "for university use, Tutorials-like materials are essential".

The structural arc of elicit, confront, resolve is explained *on page 32.*

There are even more general studies on the effectiveness of Tutorials. Direnga et al. (2018) developed the Discriminative Learning Gain (DLG), a two-dimensional measure for the comparison of pre- and post-test results that not only gives information about the average performance but also the performance difference within the investigated cohort. Direnga is currently investigating the effect of Tutorials on student performance in a 10 year longitudinal study on mechanical engineering students. Initial results (Direnga et al., 2015) indicate students' learning gain with Tutorials was significantly greater compared to traditionally taught students, especially for students that performed strongly in the Force Concept Inventory (FCI) (Hestenes et al., 1992) prior to instruction. The effect of the Tutorial was greater than other effects, e. g. the influence of the instructor or students taking an additional physics course that is taught traditionally.

The publications by Benegas and Flores (2014) and Riegler et al. (2016) painted very different pictures of the use of Tutorials. Satisfaction with the materials seems to be highly dependent on the specific situation they are used in. Direnga et al. (2018) used a much broader approach to investigate the Tutorials than the other two publications. This thesis uses yet another approach. It is less interested in the practical experience of using Tutorials or their overall effectiveness based on a general test. Instead, it investigates the effectiveness of Tutorials in helping students achieve conceptual change by allowing them to make specific observations and draw specific conclusions.

3.4 STUDENT UNDERSTANDING OF ELECTRICITY IN SECONDARY EDUCATION

Some of the studies mentioned above were partially or completely conducted with students in secondary school. Examples of these are Cohen et al. (1983); Johsua (1984); von Rhöneck (1982) and Engelhardt (1997). Since electric circuits are part of the curriculum of secondary school, high-school-level students' understanding of circuits is an area of active research.

Comparing the results of studies on high-school-level students with studies on university students generally reveals both groups to have similar or even the same difficulties. Standardized tests often can be used for both groups of students. Consequently, it is no surprise that some studies discussing general tests, like Engelhardt (1997) and Cohen et al. (1983) used university as well as high school students. The different level of detail, pace, and methods of instruction, however, can make it difficult to compare learning gains and similar measures from secondary school education with ones from university-level instruction. Thus, besides a few exceptions, this thesis does not link its findings to research on secondary school education.

4 CONTEXT OF THE INVESTIGATION

This chapter describes the settings in which data for this research project was gathered. Courses at German universities are described in general and the specific courses that are relevant for this thesis are described in detail. The way Tutorials are used in these courses is also detailed.

4.1 COURSES AT GERMAN UNIVERSITIES

There are several specifics of the German university system that have a fundamental influence on student behavior and learning. This chapter describes aspects of the German university system that are relevant to the courses investigated here. To the author's knowledge, the general statements in this section are common throughout Germany. However, it is likely that there are exceptions to most of them.

4.1.1 *Structure of the Academic Year*

Universities in Germany predominantly use a semester system with a winter semester starting in fall and a summer semester starting in spring.

Each semester starts with the *lecture period* ("Vorlesungszeit"). During this time, there are 14 weeks with lectures, labs, and recitation sections. These are interrupted by two weeks of holidays covering Christmas and New Year or one week of holidays in the week of Pentecost. The lecture period is followed by the *lecture-free period* ("Vorlesungsfreie Zeit"), which lasts until the end of the semester. At Hamburg University of Technology[1] (TUHH), exams are scheduled almost exclusively during the lecture-free period. Since about 2010 an effort was made to schedule no exams during the last six weeks of the lecture-free period in the summer semester in order to allow students to go on holidays or to work.

A student's first semester at TUHH starts with an *orientation week* ("Orientierungseinheit"), which takes place in the first week of the lecture period. During this week, diverse activities are organized by the university and student body. Regular lectures, labs, and recitation sections only start in the second week. Thus, courses for first semester students only last 13 weeks, while courses for students in later semesters last 14 weeks.

1 "Technische Universität Hamburg" in German, formerly "Technische Universität Hamburg-Harburg".

4.1.2 *Courses, Lectures, and Recitation Sections*

Although students are free to attend any course they like, they are required to complete a large amount of mandatory courses in order to graduate in their respective study programs. Most courses are only offered every other semester and many of the mandatory courses build upon each other. Thus, if a student does not attend a course in the intended semester, they are only able to attend it two semesters later, often with cascading effects on their ability to easily participate in other courses. Consequently, students in their first semesters often focus on the mandatory courses. These mandatory courses are related to the students' fields of study. Some courses on basic subjects like mathematics are mandatory for students from several study programs.

For lectures, courses at German universities are usually not split into different sections. At TUHH for example, lectures of the mandatory introductory courses are regularly attended by more than 600 students, often resulting in minimal interaction between the instructor and individual students. Possibly due to lectures being attended by everyone at the same time, 'lecture' is often used as a synonym for 'course'.

In most cases, lecturers use a *script* instead of a textbook as the basis for their instruction. These scripts are usually written by the lecturers themselves or by their predecessors. The problems used in the recitation sections are often also part of the script.

For the recitation sections, courses are usually split into groups of about 20 to 40 students. Recitation sections are often taught by a teaching assistant (TA). While some courses use graduate students as TAs, the courses investigated in this thesis use bachelor or master students as TAs. In some cases, the TAs are only two semesters senior to the students attending the respective recitation sections. Often, homework is neither collected nor checked.

Usually, attendance is not mandatory. The attendance of lectures usually drops by about 1/3 over the course of the lecture period. The attendance of recitation sections often also drops throughout the lecture period, though not necessarily as much. Many students seem to consider lectures and recitation sections as preparation for the exam. Thus, recitation sections and lectures that have no obvious relation to the expected exam are not unlikely to have a drop off in attendance of more than 1/3.

4.1.3 *Exams*

The German university system is strongly focused on exams. The credit students need for their degree is often earned by successfully completing exams, not by completing homework, or attending lectures and recitation sections. In many cases, it would almost be possible to earn a degree by passing the required exams without attending any lectures or recitation sections.

While students in Germany do not have to register for a course, at TUHH they do have to register for exams. Failing to attend an exam when registered is counted as a failed exam. Until summer semester 2017, students at TUHH who failed an exam were automatically registered for the exam next semester. At TUHH, a student who fails an exam three times automatically fails their study program. Most students who attend a lecture register for the exam in the same semester. Since lectures, recitation sections and labs are only offered every other semester, but exams can be written every semester, a failed exam will force the student to make their second attempt before they have had the opportunity to attend the lecture a second time. Only before their third attempt will they be able to attend the lecture again. Consequentially, students in their second attempt are likely to have a disadvantage.

The exams used in this thesis were all written in the semester the lecture and recitation sections of the respective course were offered. Consequently, most students who participated in the exam will have attended the respective lecture and recitation sections in the same semester. For some of the students who participated in the exams, the respective exam will have been their third attempt, for even fewer it will have been their second attempt.

To prepare for their exams, students regularly use exams from previous years. In most cases, previous exams and model solutions are made available by lecturers. Usually, copies of previous exams and unofficial model solutions are also available in student-run online repositories. Most exams are similar to the ones from previous years. While the specific problems change from semester to semester, the types of problems rarely change.

At TUHH, most exams are closed-book, but some allow students to use a limited amount of notes. Exams often last between 1 and 3 hours. The number and complexity of the tasks is often chosen so that students must be very familiar with standard approaches in order to complete the exam in time. The majority of tasks requires students to calculate numerical solutions. In a few cases, students are only scored for correct answers, but in most cases, points are given for the approach, the execution, and the result.

4.2 COURSES INVESTIGATED IN THIS THESIS

While most of the research for this thesis was conducted on students in the course EE1ME, additional data was gathered in other courses at TUHH and other universities. The respective courses are described in the following subsections. Appendix A lists the semester structure of the courses for all years that are relevant to this study.

4.2.1 *EE1ME*

The course EE1ME at TUHH is officially named *Grundlagen der Elektrotechnik* (Electrical Engineering Fundamentals). It is an introductory electrical engineering course that covers DC and AC circuit analysis and also introduces three-phase current. The course is mandatory for students in Mechanical Engineering, Naval Architecture, Process Engineering, and Bioprocess Engineering. Thus, all the students can be considered to minor in electrical engineering. The course has a duration of 13 weeks with two lectures and one recitation section per week. The lectures last 90 and 45 minutes, respectively. Starting in 2015, the recitation sections were 90 minutes per week. Before that, they were only 45 minutes. The course is taught in a traditional manner, except for two recitation section sessions and two 90-minute lectures in which students work on Tutorials. These Tutorials are *Current and Resistance*, *Voltage*, *Basic Circuit Analysis* (added in 2012), and *Phase Relations*. From 2014 on, the Tutorial *Potential* replaced the Tutorial *Basic Circuit Analysis*. The Tutorial *Phase Relations* is not discussed in this theses, while the other four are discussed in Chapters 8 and 9.

For Naval Architecture students, the course is mandatory in their first semester. For Process Engineering and Bioprocess Engineering students, the course is mandatory in their third semester. For Mechanical Engineering students who began their studies until 2014, the course was mandatory in their first semester, but for Mechanical Engineering students who began their studies in 2015 or later, the course is mandatory in their third semester. Since Mechanical Engineering students are the largest fraction of students in the course, the number of participants dropped by more than half in 2015. Since 2016, when the Mechanical Engineering students who started their studies in 2015 were in their third semester, the number of participants had risen again, though not to the numbers that were commonly reached up to 2014.[2] This long-term decrease is likely due to the fact that many students who drop out do so in their first few semesters. Consequently, the average student attending EE1ME in 2016 or later can be considered more proficient in electrical engineering than the average student attending up to 2014. Not only has their average semester increased, but they also are more likely to finish their studies. A second change that happened in 2015 is less relevant to this study. Naval Architecture students, who entered university until 2014 also had to at-

2 Since students do not formally register for courses in Germany, this description is based on the subjective impression of the author as well as the number of participants in the exam. Up to 2014, on average more than 500 students participated in the exam for EE1ME, in 2015 only about 200 students and from 2016 onwards about 400 students.

tend the subsequent EE2ME in their second semester. Starting in 2015, this course was integrated into EE1ME. However, this change of EE1ME only affected Naval Architecture students. Practically, the course is now taught in a basic and in an extended version. The basic version is identical to EE1ME before this change. The extended version has a few weeks of additional coursework. The exam for EE1ME now contains some tasks that are only mandatory for students who need the credit for the extended course.

While most exams in Germany use a free-response format, the course EE1ME switched to multiple-choice exams in 2014. The types of tasks largely stayed the same. Students still have to calculate values like voltages in circuits. Instead of handing in their full calculations, they now have to select the multiple-choice answer closest to their result. The conceptual tasks, which were part of the exam even before this change, were also adapted to this multiple-choice format. Ranking tasks for example were substituted by several questions, each asking for one individual relation. The conceptual tasks had previously often asked students to explain their reasoning. With the switch to multiple-choice questions, several possible explanations were presented in the form of two-tier multiple choice tasks (see Section 5.3.3).

For an example of a free-response test, see Appendix E.6 (p. 402).

For an example of a multiple-choice test, see Appendix E.11 (p. 424).

While the course was taught by the same instructor (instructor A) for many years, a new instructor (instructor B) took over in the winter term 2017/18. A third instructor (instructor C) took over the course in the winter term 2019/20. Instructors B and C both made changes to the lecture style and partially also to its content. The overall structure and learning goals of the course, however, were not changed.

4.2.2 *EE1EE*

The course EE1EE at TUHH is officially named “Elektrotechnik I: Gleichstromnetzwerke und elektromagnetische Felder” (Electrical Engineering I: DC Networks and Electromagnetic Fields). Similar to EE1ME, it is an introductory electrical engineering course. In contrast to EE1ME, most of the students in this course can be considered to major in electrical engineering or a closely related field. Specifically, the course is mandatory for first semester Electrical Engineering, General Engineering Science, Computer Science and Engineering, and Mechatronics students. Unlike EE1ME, EE1EE does not cover AC circuit analysis, but only DC circuit analysis. It also covers the integral notation of Maxwell’s Laws, transistors, and operational amplifiers. EE1EE is taught in a traditional manner with 135 minutes of lectures and 90 minutes of recitation sections per week over a span of 13 weeks.

4.2.3 *EE2EE*

EE2EE at TUHH is officially named "Elektrotechnik II: Wechselstromnetzwerke und grundlegende Bauelemente" (Electrical Engineering II: AC Networks and Basic Devices). The course directly builds upon EE1EE. It introduces students to AC circuit analysis as well as three-phase current and touches upon simple nonlinear and active devices. The course is mandatory for all the students for whom EE1EE is mandatory. It is taught in a traditional manner with 135 minutes of lectures and 90 minutes of recitation sections for 14 weeks, but by a different instructor than EE1EE.

4.2.4 *EE3EE*

The course EE3EE at TUHH is officially named "Elektrotechnik III: Netzwerktheorie und Transienten" (Electrical Engineering III: Circuit Theory and Transients). The course covers circuit theorems and general n-port circuits as well as transient analysis in time and frequency domain. It is mandatory for Electrical Engineering, Mechatronics, and some General Engineering Science students. The course incorporates demonstration experiments as part of its lectures. It is taught in a traditional manner with 135 minutes of lectures and 90 minutes of recitation sections for 14 weeks by an instructor different than the ones from EE1EE and EE2EE.

4.2.5 *EE1UK*

The course EE1UK is an introductory electrical engineering course at Loughborough University in the United Kingdom (UK). It is officially named *Electrotechnology* and mandatory for students in the fourth semester of the Automotive Engineering and Aeronautical Engineering study programs. While EE1UK is the first university course on electrical engineering in these two study programs, students seem to have have considerable knowledge from school. This is likely due to the admission process, which requires all students to have A-level Physics, most often with an A grade[3]. The course covers basic DC and AC circuit analysis, electric motors, power electronic, frequency domain, filters, as well as nonlinear circuit elements. The course uses traditional lectures and exercises, but also elements of interactive engagement like for example a mobile game based on a circuit simulation tool. The course also used several worksheets from the *Tutorials in Electrical Engineering* (Kautz, 2010), which had been translated into English. Amongst these were the Tutorials *Current and Resistance*, *Voltage*, and *Potential*.

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3 Based on personal communication with the instructor.

4.3 USE OF TUTORIALS AT TUHH

Tutorials are intended to be used during recitation sections. Yet, in the context of this investigation, they were also used during lecture time. This section describes the use of Tutorials in both settings.

The concept and structure of Tutorials are described in Section 2.3.4 (p. 26).

4.3.1 *Tutorials in Recitation Sections*

The two Tutorials *Current and Resistance* and *Voltage* are used in recitation sections of the course EE1ME. Each section with about 20 students attending is taught by a TA, who is a bachelor or master student. These TAs also teach the recitation section in weeks where no Tutorial is used. They are prepared for the Tutorial sessions during the regular preparation meetings. Some TAs are not very supportive of Tutorials[4], possibly because they see more value in traditional recitation sections for which they have less time due to the Tutorial or because they are simply unfamiliar with the concept of Tutorials. Depending on their study program, some TAs might have never experienced a Tutorial from the student perspective.

The Tutorials are reproduced in full in Appendix B (p. 309). The research on these two Tutorials is presented in Chapter 8 (p. 177).

To support the regular TAs during the recitation sections in which Tutorials are used in EE1ME, an effort is being made to assign at least one additional TA to each section. This additional TA is a student attending a course on engineering education, taught by members of the Engineering Education Research Group (EERG), which the author of this thesis also belonged to. The course covers different aspects of engineering education, focusing on conceptual understanding and instructional methods to foster active learning. One of these methods are Tutorial worksheets, which the participants experience from both the student's and the instructor's perspective. Due to scheduling issues and a varying number of participants, some recitation sections in EE1ME have no additional TA assigned.

The author participated in some of these recitation sections as a TA and briefly visited other sections to check if there were any problems. The Tutorial *Current and Resistance* was used in the first recitation section of the course EE1ME. As students in Germany do not have to register for courses or simply may go to an incorrect room, single recitation sections sometimes had more students attending than intended. Still, TAs were able to manage such situations. Overall, the Tutorials in EE1ME were used by students and supported by TAs as intended.

An overview of the weeks different Tutorials were used in the courses investigated here is provided in Appendix A (p. 305).

In the course EE1UK, Tutorials were used during a 2 hour time slot with 50 students and 2 instructors. Thus, the number of students per instructor in EE1UK was similar to that in EE1ME. The larger size of the overall group, however, has similarities with the use of Tutorials in a lecture hall setting.

4 Based on personal communication with former TAs of EE1ME.

Figure 4.1: Use of a Tutorial in a classroom setting at TUHH. Four TAs can be seen standing in front of groups of students. The instructor of the course can be seen in the middle of the picture, talking with a group of students while leaning over from behind.[5]

4.3.2 *Tutorials During Lecture Time*

The course EE1ME also uses two Tutorials in a lecture setting. A use of Tutorials in lectures is usually not recommended, as the lecture room setting can strongly reduce the effectiveness of a Tutorial. Several measures were taken to counteract the negative effects of this setting. These effects and measures are described below.

During Tutorials, students are usually asked to work in groups of three or four, preferably seated around a table to foster interactions in the group. The seats in lecture halls usually have fixed tables and cannot be turned (see e. g. Figure 4.1). Consequently, it is difficult for students to turn around and work with students in the row behind them. To still allow for effective group discussions, students were asked to form groups with up to two neighbors *in their row*. These groups ensure that students can work with the printed Tutorial in front of them and at the same time communicate with their group in the noisy classroom environment.

Different suggestions for the number of students per TA are listed in Section 2.3.4.1 (p. 27).

Lectures are very cost efficient, since one instructor can lecture hundreds of students at the same time. Tutorials, in contrast, require a higher instructor-to-student ratio of 1 to 25 or even 1 to 15, depending on the source. This high instructor to student ratio is required, as TAs have to regularly discuss concepts and answers with each group of students working on a Tutorial. Thus, when a Tutorial is used in a lecture room, a large number of TAs has to be used. At TUHH, at least 1 TA was available for every 40 students. In addition to the regular instructor of the course and members of the EERG, these again were participants of the course on engineering education described in the

5 Picture taken by Viktoria Constanze Schneider.

previous section. While an even better ratio of instructors to students certainly would not have been detrimental, the ratio of 1 to 40 seemed to be sufficient. As the instructors were not assigned to a certain section of the room but helped where needed, it was usually possible to quickly help groups who asked for assistance. Additional summaries also helped to remove the necessity of longer discussions, as described below.

Some groups tend to be hesitant about calling a TA when they have trouble answering a question in a Tutorial. To compensate, TAs regularly visit every group. As there usually only is a small number of groups in a recitation section, a TA in such a section usually is able to monitor the progress of every group and ensure that they all reach the most important parts of a Tutorial. When required, the TA might help a group that is too slow or even tell them to skip certain less crucial tasks. In a large lecture room setting, where multiple TAs are present at the same time, it is much more difficult to keep track of every group. Thus, at regular intervals during Tutorial sessions in lecture rooms, key results were summarized in front of the whole class.

To help instructors reach each group, students were asked to leave every third row empty. This seating allowed TAs to reach every student either by standing in front of them or by leaning over from behind (see Figure 4.1).

5 METHODOLOGY & METHODS

As stated by its title, the goal of this thesis is to investigate *engineering students' understanding of basic electric circuit concepts and the effect of qualitative worksheets*. The investigation consists of three aspects: (1) determining *if* students correctly understand relevant concepts and are able to solve problems using these, and if that is not the case (2) finding *how* students misunderstand these concepts and (3) identifying (sets of) tasks that help students to arrive at an improved understanding. These three aspects of the investigation are also reflected in the research questions RQ 1, RQ 2, and RQ 3, which were introduced in Chapter 1.

This current chapter not only introduces various research methods used for the investigation, but also outlines its *methodology*, i. e. why methods were selected. While the methodology is often not explicitly addressed in engineering research, the wide range of methodological approaches in educational research warrants a deliberate and thus deliberately expressed decision about the methodology. After all, the selection of a certain set of methods determines what kind of answers a study can and cannot find. The methods discussed here are *research* methods. They are largely independent of the *educational* methods that are used for instruction.

The educational methods used in the context of this investigation are described in Chapter 4 (p. 51).

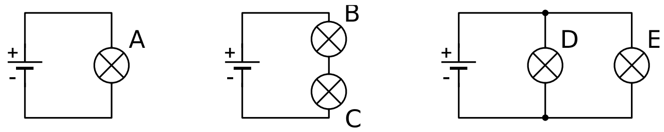
The research methods and methodology presented in this chapter are used throughout the thesis and help to probe students' conceptual understanding (see Section 2.3). Methods that are only used at one point in the thesis, especially the methods required for Decoding the Disciplines (Section 2.4) and APOS-Theory (Section 2.5) are introduced where needed.

5.1 CONCEPTUAL QUESTIONS

It might seem simple to investigate aspect (1), i. e. determining *if* a student correctly understands a concept or is able to solve problems using it. However, two obvious approaches, asking the student directly and using standard quantitative problems, are prone to false positive results.

Directly asking a student to explain a concept often results in textbook answers. As shown in the examples in Section 2.3.3.1 (p. 22), students are often aware of the way concepts are taught in class and able to answer accordingly. Especially in formal tests it is likely that students give the answer they think is expected of them instead of the one they believe to be true, resulting in false-positive results.

The following three circuits contain identical bulbs and identical ideal batteries. (Assume that the batteries are ideal voltage sources, i.e. they have no internal resistance.)



Rank the 5 bulbs by their brightness.
(Please use the relational operators '>', '<', and '='.)

Figure 5.1: Five-bulbs test, as used in this thesis.

The other obvious approach to test student understanding is the use of quantitative problems, like the ones found at the end of many textbook chapters and in many exams. As Mazur (1997) explains, "it is possible for students to do well on conventional [quantitative] problems by memorizing algorithms without understanding the underlying physics" (p. 6). "Students tend to perform significantly better when solving standard textbook problems than when solving conceptual problems covering the same subject" (p. 6). Thus quantitative problems would also lead to false-positive answers that incorrectly indicate that a student has *understood* a concept when they have simply memorized an algorithm.

To investigate if students have correctly understood a problem, this research project employs conceptual questions. In general, these questions are framed so that students have to use the relations between different quantities instead of equations to determine the correct result. Consequently, these questions allow to test students' understanding of the tested concepts instead of students' ability to apply algorithms.

If possible, questions are designed so that the concept being tested is not obvious to students. When students cannot identify the concept being tested, they are unable to give the answer they think is expected of them. Thus, questions designed that way allow researchers to identify students' understanding of the concepts being tested instead of their ability to provide the expected answers.

The five-bulbs test is discussed in detail in Section 7.1 (p. 106).

Figure 5.1 shows the five-bulbs test as an example of such a conceptual question. As this question does not provide any numerical values and bulbs in general have a nonlinear current–voltage characteristic, students cannot use standard questions from circuit analysis to answer it. The question is used to identify student misconceptions regarding current, e. g. the misconception that current is "used up", as well as the behavior of batteries, which some students believe to behave as ideal current sources. To students, however, it will not be obvious that their understanding of sources and current, especially the misconception of current being "used up", is tested. The question simply asks students to rank bulbs by their brightness and does not mention current or voltage.

Different types of conceptual questions are described in Sections 5.3.2, 5.3.3, and 5.3.4. Appendices E and F list all questions used in this research project and thus provide many examples.

5.2 METHODOLOGY OF THIS THESIS

Many research projects in engineering education research originate from informal observations of students in the classroom. However, as Beichner (2009) quips in his *Introduction to Physics Education Research*, "the plural of anecdote is not anecdata". Rigorous engineering education research may start with informal observations, but always requires hard data on students and their understanding. Only with such data, trends and phenomena that affect all students or large groups of students can be identified rigorously.

To gather such hard data, this study employs quantitative educational research methods, such as multiple-choice tests and ranking tasks given to a whole population at once. Their results provide a substantial statistical power (Beichner, 2009). They can be generalized and validated at replication sites relatively easily, as the test materials can simply be copied. With these types of tests, it is possible to investigate aspect (1), the number or fraction of students which have correctly understood a concept and are able solve conceptual problems using it.

The three aspects this thesis investigates were named on page 61.

This study also employs qualitative methods like interviews and free-response questions, to investigate aspect (2), how relevant concepts are (mis)understood by students. These methods allow for a finely grained analysis of *what* students think. They therefore allow to answer *why* students believe a certain answer to be correct and to verify that a student did not simply exclude all other answering options in a multiple-choice question.

Data gathered with qualitative methods are always in respect to individual students. While the results of qualitative studies can certainly be generalized by assuming that there also are other students who think similarly, the labor required to conduct such studies often prohibits researchers from gathering large datasets. Thus, qualitative studies cannot be used to determine the fraction of students who think a certain way.[1]

1 It could be argued that a question asking for a number already implies quantitative research. While that might be the case, the point still stands: It is rarely possible to conduct individual interviews on a large scale.

To estimate the frequency of certain misconceptions, this study employs a mixed-methods approach, combining qualitative and quantitative methods (Beichner, 2009). The quantitative methods are used to analyze which problems are difficult for most students. The nature of these difficulties is then further investigated using qualitative methods. When difficulties are identified, their frequency can then in turn be investigated using quantitative methods.

To investigate aspect (3), identifying tasks and sets of tasks that help students to achieve a conceptual change, quantitative methods can be used again. Student performance is measured before and after an intervention. When the pre- and the post-test are similar enough, their results can be compared directly, allowing for the measurement of student learning during the time of the intervention. If there is significant learning even though the only relevant difference between the pre- and post-test was students' participation in the intervention, the task or set of tasks used in the intervention must have helped students understand relevant concepts. The intervention can thus be considered a success.

Mixed-methods might seem like the perfect approach for educational research. However, the limited time available for any research project puts a limit on the data that can be gathered. In most cases, data on student learning can only be collected once a year, when students are at a certain point in their studies.

Often, the specific difficulties of students are not known at the beginning of a research project, making it impossible to design test questions that clearly differentiate between relevant conceptions or highlight misconceptions. After initial data has been analyzed, students' conceptions and misconceptions can be understood better. An improved understanding of these conceptions and misconceptions will in turn allow for the design of better test questions. These questions can again refine the understanding of students' conceptions and misconceptions, and so on. This iterative approach is often necessary in discipline-based educational research (DBER) and labeled as *grounded theory* by some researchers (see e. g. Van De Bogart, 2017).

As only a limited number of iterations is possible due to the specific points in time when data can be gathered, and different aspects of student understanding are uncovered at a different pace, the different aspects of a research project often reach different levels of refinement.

5.3 QUANTITATIVE METHODS

Most datasets for this research project were quantitative in nature. Section 5.3.1 will describe the different conditions under which these sets of data were gathered. Subsequently, Sections 5.3.2 to 5.3.4 will describe the different formats of questions used to gather quantitative data. Different considerations for the design of these tasks will be described. Finally, Section 5.3.5 will describe different methods for the analysis of the quantitative data gathered in this study.

5.3.1 *Written Tests*

The source of data used most in this study are written tests. While some of these tests were exam questions, the majority were ungraded quizzes given to students during lecture time. One advantage of both, quizzes and exams, is the large number of students about whom data can be collected at the same time, resulting in a minimized sampling bias and in results with substantial statistical power. Both ungraded quizzes and exams have benefits and limitations that must be considered.

Unlike exams, quizzes can be given at any time during the semester. Thus, quizzes allow for a much finer control of what students have and have not been taught before the quiz is used. They can, for example, be used directly before and after an intervention. When quizzes are ungraded, they offer several other benefits. Most importantly, there is no incentive for students to cheat or guess an answer. Thus, the results of ungraded quizzes likely are a better representation of what students *actually believe*. Additionally, ungraded quizzes do not have to satisfy as many requirements as exams regarding fairness etc. When a task in an exam is for example answered incorrectly by every student, this task might reveal valuable information about students' abilities or understanding. Exams, however, often require students' scores to be spread to a certain degree in order to allow a reliable mapping onto a grade scale.

In general, exams provide a more serious atmosphere, allowing students to better concentrate. Students have to work on their own during exams, which is strictly enforced. Students usually are prepared, i. e. have revisited the course materials. Additionally, due to the grades depending on mostly exam results, students have an incentive to perform as well as they can.

Ungraded quizzes used in this research project usually consist of only one double-sided piece of paper with two or three tasks. At the beginning of a quiz, students are told the expected duration of the quiz, usually 10 minutes. During the quiz, instructors walk through the room. When required, they remind students to work on their own. The instructors observe how many students have finished the quiz. When a substantial number of students has not finished after the initially announced duration, the time for the quiz may be extended. This flexible duration ensures that most of the students who in principle are able to solve the problems presented in the quiz can do so and only students who are unsure or require an extraordinary amount of time are not able to finish the quiz.

This research project also used written tests in the form of exam questions. These questions were usually one of about six questions that students had to answer in their exam. Like most of the exams at Hamburg University of Technology[2] (TUHH), these were written under a time constraint. Since the questions used for this study usually were the first task in an exam, they were usually answered by almost all students. As previous exams are published and the types of tasks rarely change, students were able to use old exams to prepare for these tasks. Consequently, tasks that were particularly similar to previous ones were usually answered correctly by many students. The exam questions were developed by the author of this thesis in coordination with the instructor of the course, who ensured that the task aligned well with the learning goals of the course.

5.3.2 *Multiple Choice Questions*

A common type of conceptual questions for quantitative research are multiple-choice single-selection questions in which students have to select *one* of several answering options.

A multiple-choice question consists of the problem set-up, also called the *stem*, and the answering options. The answering options consist of one correct answer, called the *key*, and one or more incorrect answers, called *distractors*. Multiple-choice questions can be evaluated using a scanner and software, as there is a set of pre-defined answers of which only one must be selected. As processing by hand also does not take much time and most tests used in this research project had only a few hundred participants, all tests that are used in this thesis were evaluated by hand.

When not phrased carefully, the stem or general intent of a question can be unclear to students. In the case of free-response questions, where students are supposed to write a text, unclear or confusing questions can sometimes be identified based on students' answers. In some cases, students even explicitly state their confusion. The same is not possible with multiple-choice questions. Consequently, multiple-choice questions put a higher burden on their author. The author has to take care that each question's stem, the key, and the distractors are understood correctly by each student. Ideally, each question is validated through think-aloud interviews or similar methods. However, due to the effort required for such a validation, only multiple-choice questions in standardized tests are validated that way. For investigations like the one in this thesis, the validity of the questions depends on the experience of the question's author. A partial ex post facto validation can be performed based on free-response explanations (see Section 5.4.1).

2 "Technische Universität Hamburg" in German, formerly "Technische Universität Hamburg-Harburg".

The distractors must be paid special attention. Firstly, students should not be able to identify the correct answer based on test-cleverness, i. e. their ability to identify patterns in the test or the answering options. Therefore, all answering-options should (1) have a similar level of detail, which can often be measured by their length. They should also (2) match the stem in respect to grammar as well as choice of words, be (3) mutually exclusive, and (4) equally believable.

In general, multiple-choice questions with more answering options will have a lower chance for students to guess the correct answer. Many tests, such as the DIRECT version 1.1 and above (Engelhardt, 1997) or the FCI (Hestenes et al., 1992) use five answering options, resulting in an average score of 20% for a student who guesses every answer. The use of more answering options is rarely advised as too many answering options require high cognitive load. Some researchers[3] recommend to use even less answering options, arguing that most questions only have two or three believable options and that bad distractors are rarely selected anyways.

When logically possible, multiple-choice questions that were used in exams and part of this research project offered five answering options, to prevent students from passing an exam by guesswork. Multiple-choice questions that were used in quizzes offered one distractor for each common misconception. Thus, the number of answering options was determined by the number of misconceptions related to the concept being tested. When a question had a set of logically possible answering options, such as a current *decreasing*, *increasing*, or *staying the same*, all of these options were offered as an answering option. This selection of answering options ensured every student found an option that matched their belief. As students could simply select the answers that matched their belief instead of first checking the possible answering options, this selection also reduced cognitive load.

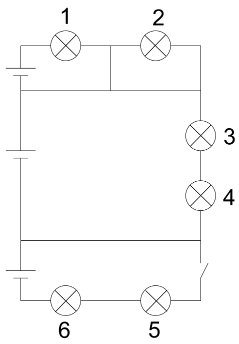
5.3.3 *Two-Tier Multiple-Choice Questions*

As described in Section 5.1, this research project uses conceptual questions to investigate student understanding. The multiple-choice questions described above ask students to state the relation between two quantities in a given circuit or the change of a quantity when the circuit is modified. Usually, these questions are designed so that each answer aligns with one specific reasoning or misconception. However, in some cases direct data about students' reasonings is desirable, either to check if the answering options actually align with the misconceptions they are supposed to match, or when several misconceptions result in the same relation between quantities or change of one quantity. While qualitative research (see Section 5.4) can be used in these

3 personal communication

Task 1
The three batteries in the circuit at right are identical and can be treated as ideal voltage sources. The long line indicates the positive terminal of a battery. All six bulbs are identical and all occurring voltages are within operating range of the bulbs.

The switch is open.



Task 1.1 (2 points, if both answers are correct)

Task 1.4 (2 points, if both answers are correct)

Task 1.4.1	**The voltage at the switch is**
A	equal to 0 V
B	larger than 0 V but less than one battery voltage
C	equal to one battery voltage
D	larger than one battery voltage

Task 1.4.2	**because**
A	without current there can be no voltage
B	there is no voltage at bulbs 5 and 6
C	$V = R \cdot I$ applies with $I = 0$ A
D	there are three batteries in the circuit
E	a third of the voltage drops at each of the bulbs and the switch, respectively

Figure 5.2: Example of a two-tier multiple-choice question. The full test is shown in Appendix E.18.

cases, two-tier multiple choice questions offer an approach that also works with large numbers of students.

Two-tier multiple-choice questions consist of two sub-questions, each itself a multiple-choice question. The first tier, i. e. question, is identical to the type of multiple-choice questions described above. The second tier asks students to choose one of several statements to justify their answer in the first tier.

As described in detail in a separate publication (Timmermann and Kautz, 2015a), two-tier multiple choice questions can be designed to reveal students' reasonings without explicitly asking for these. The first tier of such a question requires a fact-based response while the second tier asks students to select one of a few explanations in the form of simple, factual statements. An example for such a question is shown in Figure 5.2. Timmermann and Kautz (2015a) describe the design of such questions in detail and use exam results to show that while these questions are more difficult than single-tier multiple-choice questions, they better differentiate between students who overall are strong and weak.

The data from Peşman and Eryılmaz is discussed in Section 7.6.2 (p. 161).

The data from Sabah is briefly discussed in Section 7.4.1.1 (p. 135).

Sometimes, three-tier multiple-choice questions are used, where the third tier asks students how certain they are of their answer. Peşman and Eryılmaz (2010) developed such a test. Sabah (2007) developed a two-tier test that asked students to rate their confidence separately for each tier.

5.3.4 *Ranking Questions*

Ranking questions have been used for a long time in engineering education research (EER). The five-bulbs test shown in Figure 5.1 had for example been published by McDermott and van Zee in 1985. Ranking questions ask students to rank a set of objects by one of their properties. They combine several positive aspects of multiple-choice and free-response questions. Similarly to multiple-choice questions, they require the answer to be in a specific format. This specificity has two benefits. Firstly, it reduces the complexity of the task for students, as they do not have to decide how to format or phrase their answer. Secondly, the specific format makes it possible to automatically evaluate student responses. Similarly to free-response questions, ranking questions provide students some degree of freedom, as they allow for partial answers and an arbitrary ordering of the individual parts of the answer.

An algorithm for the automated evaluation of rankings is described in Section 6.2 (p. 95).

5.3.5 *Statistical Evaluation of Categorical Data*

Most of the data collected in this research project is categorical in nature. In multiple-choice questions, students select one of several answers. The frequency of each answer can be recorded, but as the different answers to such a question are not related numerically, no average value can be calculated. For ranking questions, the frequency of each unique ranking or of certain relations within the rankings can be recorded. These also are not related numerically and do not allow for an average to be calculated.

In many cases, for example when determining the frequency of misconceptions, it is sufficient to list and compare the frequencies of the individual answering options. Sometimes these frequencies are averaged over multiple cohorts. Yet in other cases it is necessary to compare the difference in answers of two cohorts or to assess how a cohort's answers changed over time. Then, statistical tests can be used to determine the significance of such differences and changes. Some of these tests are explained below.

5.3.5.1 *Pearson's χ^2 Test*

While it can be used in other cases, in this thesis, Pearson's χ^2 test is only applied to 2×2 contingency tables. An example for such a table is shown in Table 5.1a. One dimension in these contingency tables is always used to distinguish the cohorts, in Table 5.1a students that had participated in 1 vs. 2 Tutorials. The other dimension is the criterium that is to be investigated, in Table 5.1a if the ranking given for the question shown in Figure 5.1 was correct or incorrect.

Pearson's χ^2 test can be used to calculate the probability that the *observed* occurrences of the category-combinations occurred randomly

Table 5.1: Example of a 2×2 contingency table: Dependence of five-bulbs test results (see Figure 5.1) on the number of Tutorials for students in the course EE1ME in 2016. Given are (a) the original table, formatted as in the remainder of this thesis, as well as (b) the observation values O_{ij} including the column and row sums and (c) the expectation values E_{ij} that can be calculated from O_{ij}.

(a) Original table

	No. of Tutorials	
Ranking	1	2
correct	76	44
incorrect	117	30

(b) Observation values O_{ij}

		j = 1	j = 2	Σ
i	1	76	44	120
i	2	117	30	147
	Σ	193	74	267

(c) Expectation values E_{ij}

		j = 1	j = 2	Σ
i	1	86.7	33.3	120
i	2	106.2	40.7	147
	Σ	193	74	267

under the null-hypothesis that the two categories were statistically independent. If this percentage is low, the null-hypothesis is rejected, implying that the two categories are statistically dependent. In the case of Table 5.1a it is observed that students who participate in more Tutorials also rank the bulbs in Figure 5.1 correctly more often. As the null-hypothesis is rejected with $p(\chi^2) = 0.004 < 0.05$, it can be assumed that the observation is not made due random chance, but that there is some relation between the number of Tutorials a student has participated in and their ability to correctly rank the bulbs.

Table 5.1b shows the observation values O_{ij} for the data in Table 5.1a as well as the sum $O_{\Sigma j}$ for each column j, i.e. the size of each cohort, and the sum $O_{i\Sigma}$ for each row i, i.e. the overall number of correct and incorrect rankings. $O_{\Sigma\Sigma}$=267 is the number of all observations listed in the table. Based on these sum values, the expectation values can be calculated as $E_{ij} = O_{\Sigma j} \cdot O_{i\Sigma} \,/\, O_{\Sigma\Sigma}$, assuming that the two categories (here: number of Tutorials and the ranking being correct) are independent. Pearson's χ^2 test determines the probability that the differences between the expected values and the observation values can be explained by a drawing error, i.e. chance. To perform the test,

$$\chi^2 = \sum_i \sum_j \frac{(O_{ij} - E_{ij})^2}{E_{ij}}, \tag{5.1}$$

is calculated (Bortz and Schuster, 2010, p. 138). The resulting probability can be determined using tabular values for the χ^2 distribution with 1 degree of freedom in the case of a 2×2 contingency table (e.g. Bortz and Schuster, 2010, p. 588).

Pearson's χ^2 test should only be used for sufficiently large data sets with all $E_{ij} > 5$ (Bortz and Schuster, 2010, p. 141). For smaller cohorts or more extreme distributions *Fisher's exact test* can be used, which also illustrates the idea behind the χ^2 test.

5.3.5.2 *Fisher's Exact Test*

Fisher's exact test is an alternative to Pearson's χ^2 test. It has no requirements regarding the size of the population. With Fisher's exact test, the probability for the independence of the two categories is calculated directly. The probability of every possible contingency table with $O_{\Sigma\Sigma}$ observations is calculated based on $O_{\Sigma j}$ and $O_{i\Sigma}$. The probabilities of all contingency tables that are more extreme than the observed one are then added up to determine p.

For contingency tables with large $O_{\Sigma\Sigma}$, the number of possible contingency tables quickly becomes too large to be numerically feasibly. However, in cases where Pearson's χ^2 test should not be employed due to small E_{ij}, Fisher's exact test can often be used.

5.3.5.3 *McNemar's Test*

In the two tests described above, no student was counted twice. Either completely different cohorts of students were compared or one cohort was split using a criterium like the number of Tutorials students had participated in, effectively resulting in two smaller cohorts. When the change in a cohort is investigated using a pre- and post-test, Pearson's χ^2 and Fisher's exact test cannot be used. In such cases, McNemar's test must be used. As described by Bortz and Schuster (2010, p. 147), the contingency table looks the same but χ^2 is calculated as

$$\chi^2 = \frac{(O_{12} - O_{21})^2}{O_{12} + O_{21}}. \tag{5.2}$$

The resulting probability can again be determined using tabular values for the χ^2 distribution with 1 degree of freedom in the case of a 2×2 contingency table (e. g. Bortz and Schuster, 2010, p. 588).

5.4 Qualitative Methods

To investigate how students misunderstand relevant concepts, qualitative research methods are used. Two such methods are described below.

5.4.1 *Student Explanations*

Several questions ask students to "briefly explain your reasoning". These questions are used for two different purposes. Firstly, the explanations can be used to check the supposed match between students' answers and their beliefs. The relation $B \neq C$ in Figure 5.1 for example is seen as an indication for students believing current is "used up". The explanations of students that gave such an answer can be used to verify this assumption. While certainly not every student will state so explicitly, a reasonable fraction of students who gave the answer $B \neq C$

should also give the explanation that current is being "used up". Secondly, the explanations can in general be used to identify student reasoning patterns and individual reasonings, possibly revealing new misconceptions.

To analyze student reasonings, their explanations are coded into groups of similar statements. In most cases, this process is iterative and starts with the researchers reading a set of explanations to define initial codes. All explanations are then assigned one of these initial codes. The codes must be so broad that their overall number is feasible, but specific enough to be meaningful. Often, explanations that are rare or unclear are grouped in the code "*other*" to decrease the number of overall codes. When they are of importance, even rare explanations are kept as a separate category. If there are too many codes or the codes turn out to be too broad, the codes are revised and the explanations are coded again.

5.4.2 *Individual Semi-Structured Interviews*

The most in-depth method of data collection for this thesis are semi-structured interviews.

Interviews are a common method of qualitative research. There is a wide spectrum of ways interviews can be conducted and there are multiple methods to extract data from interviews. The subsequent description reflects the style of interview and analysis of data that was considered best suited for this research project.

The interviews were semi-structured, i. e. each interview broadly followed the same structure. The tasks used in the interviews were developed beforehand and students were presented each task in sequence. While the initial questions with which students were introduced to each task were practically identical, the follow-up questions were varied as necessary to fully understand each student's reasoning. Only when the interviewers were satisfied with their understanding of a student's answer, they continued to the next task. While the structure given by the set order of tasks ensures that students' answers could be compared, the student-specific questions allowed for an in-depth analysis of each student's individual understanding, thereby playing to the power of interviews.

Students are interviewed individually, i. e. not in a group, as individual interviews best suit the goal to acquire a detailed picture of each student's understanding. In most cases, two, sometimes three interviewers participated in an interview. The larger number of interviewers increased the likelihood that at least one interviewer found a suitable question to elicit the interviewee's understanding and allowed one interviewer to prepare an impromptu question while the other continued the conversation.

During their interview, students were not told if their answers were correct. The goal of the interviews was to produce detailed records of students' mental models. Thus, every answer that illustrated a students' mental model helped to reach the goal of the interviews, even if the answer did not align with expert opinion. After giving an answer, students were often asked about similar situations. These questions were intended to determine how dependent a student's mental model was on the specific situation and if the student recognized a possible contradiction. Such questions were also asked if a student gave a correct answer. Thus, it was difficult for students to know during the interview, if their answers were correct. After the interviews, students were given feedback on their answers.

The interviews contained tasks with circuit diagrams. It was expected that students would point at parts of these diagrams and write down equations or draw sketches to illustrate their answers. To record where a students pointed while answering and at what point in the interview a student wrote something, the interviews were recorded on video. After the interviews, the videos were transcribed. These transcriptions noted where a student pointed or when they wrote something important.

The interviews contained several questions. Each of the topics addressed in the interviews was analyzed separately. For each topic, the statements and answers of each student were summarized to characterize their mental model. These included not only if their answer was correct, but also their descriptions of the physical quantities, wether or not they changed their answer during the interview, and how sure they seemed of their answer. This process of abstraction was based on both the transcript and video recording and in most cases required multiple iterations. These summaries were then used to determine the different mental models students used. Finally, suitable quotes summarizing each mental model were extracted from the interview transcripts, when possible.

CONTRIBUTIONS TO RESEARCH METHODS, EMPIRICAL EVIDENCE, AND ANALYSIS

6 EXTENSION OF EDUCATIONAL RESEARCH METHODS

The previous chapter described various methods used in engineering education research. Since all of these methods are well established, the previous chapter mostly consisted of a summary of the methods and their use cases. Two methods that are important for this thesis, however, were developed or fundamentally extended as part of it. These methods are described in this chapter.

6.1 MATCHING TESTS USING SELF-GENERATED IDENTIFICATION CODES[1]

When conducting longitudinal studies in educational research, it is often important to not only compare the average test scores of a cohort at two or more points in time, but to analyze how test results of individual students change over time. Such an analysis can be important when (1) the individuals in the investigated cohort cannot be expected to behave similarly, (2) the composition of the cohort changes over time, possibly introducing a bias, or (3) not all members of the cohort are treated the same. While aspect (1) can never be fully excluded, aspects (2) and (3) are particularly relevant for this thesis.

Many of the tests used in this thesis were conducted during lecture time. As attendance is not mandatory in the courses investigated, the number of students attending lecture changes dramatically throughout the semester. It is not unlikely that primarily the weaker students stop attending lecture, which would introduce a bias in pre-post-comparisons. Additionally, students who had participated in an intervention described in Section 9.6 needed to be distinguished from ones who had not.

To analyze how an individual student's test results change over time, an identifier has to be added to the test results. Up to 2015, the Engineering Education Research Group (EERG) at Hamburg University of Technology[2] (TUHH) used matriculation numbers as an identifier in some standardized tests. These were not a satisfactory solution since the standardized pre-post-tests were supposed to be anonymous but required students to fill in their matriculation number as

1 The work described in this section was conducted in collaboration with Julie Direnga. Parts were previously published in Direnga et al. (2016).

2 "Technische Universität Hamburg" in German, formerly "Technische Universität Hamburg-Harburg".

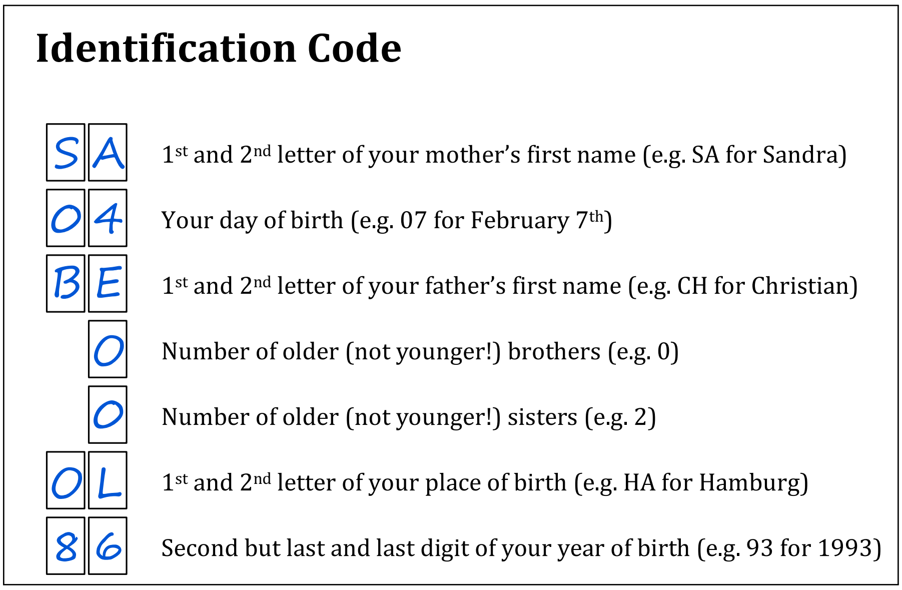


Figure 6.1: Filled in SGIC used for tests by the EERG at TUHH. The responses written in blue result in the identification code `SA04BE00OL86`.

the identifier. Since lists containing student names and matriculation numbers are frequently used in Germany, the tests could not be considered anonymous. Based on their feedback, students were aware of this problem. Likely because of this lack of anonymity, some students did not volunteer their matriculation number or stated obviously fake numbers when answering the test.

The matching rates using matriculation numbers as identifiers were overall not as high as desired. Of over 5000 pre- and about 3500 post-tests gathered in different courses at TUHH, only 72% of post-tests could be matched to a pre-test. To ensure anonymity, investigations using non-standardized tests, like the ones in this thesis, did not use any identifiers. With the goal of increasing matching rates and ensuring anonymity, the EERG at TUHH switched to self-generated identification codes (SGICs) in 2015.

SGICs are identification codes that the participants of a test generate themselves. They were first suggested by Carifio and Biron (1978) and have been used by many researchers since. The terms used in the context of SGICs are diverse, sometimes the abbreviation SGIC even stands for “subject-generated identification code” (see e. g. Damrosch, 1986). The terms used in this section do not follow those of a specific publication on the subject, but were selected to fit with the other terms used in this thesis.

When answering a test with a SGIC, participants not only answer regular questions on subject matter, but also a set of *coding questions* as the ones shown in Figure 6.1. Their *responses* to these coding questions (blue font in Figure 6.1) form their *identification code*, when “read as one word". The identification code for the example shown in Figure 6.1 is `SA04BE000L86`.

Based on an algorithm, the identification codes of all pre- and post-tests are compared and tests that have identical or similar codes are matched. The similarity required for codes to be considered a match depends on the type of matching. With *exact matching*, two codes are only matched if they are identical, with *1-off matching*, codes can also be matched when they differ in one place. With *2-off matching*, they can differ in two places. The percentage of post-tests matched to a pre-test is called the *matching rate*. The percentage of post-tests incorrectly matched to a pre-test is called the *collision rate*. The matching rate is the sum of the collision rate and the percentage of post-tests matched to the correct pre-test. Two important aspects must be optimized with every SGIC:

Firstly, if one person participates in both the pre- and post-test, their tests should be recognized as belonging to the same person. To determine if a given SGIC satisfies this requirement, test participants would have to be identified unambiguously. Such an unambiguous identification would either require a complex setup, like markers that students needed to keep between the pre- and post-test, or would have to rely on official documents. Both approaches were considered problematic in the present setting. Instead, the matching rate was used as an indicator for this first aspect being met, with tests correctly identified as belonging to the same person increasing the matching rate. The matching rate, however, also increases with an increased number of false positive matches. An important factor to achieve a high matching rate is to ensure that the participant's responses to coding questions do not change over time. A larger number of coding questions will increase the likelihood of changes occurring somewhere in a code. Using 1-off or even 2-off matching instead of exact matching can mitigate such errors and increase the matching rate.

As a second aspect, tests handed in by different participants must be recognized as belonging to different participants. When the identification codes of different participants are considered as equal, these codes are said to *collide*. To prevent collisions, each participant in a test must have a unique identification code. The likelihood of unique identification codes can be increased by increasing the number of coding questions and by selecting coding questions with a large variation in responses. Switching from exact to 1-off or even 2-off matching increases the collision rate.

Consequently, a compromise must be found between a high matching rate and a low collision rate. This compromise can be influenced by the selection of the coding questions as well as the type of matching (exact, 1-off, 2-off). The following section details the selection of coding questions for the SGIC that was introduced by the EERG at TUHH. Section 6.1.2 presents an analysis of the likelihood of *collisions* with the selected coding questions. Sections 6.1.3 to 6.1.5 describe the algorithm developed for the matching process and present an analysis of the best type of matching. Sections 6.1.6 and 6.1.7 present a generalized estimation of collision rates.

6.1.1 *Selection of Coding Questions*

As described above, the selection of the coding questions is a key factor for the quality of a SGIC. While it might seem trivial to select coding questions, there actually are many criteria that determine their quality. Different authors have listed different criteria. The following list is a compilation of the criteria considered by Julie Direnga and Dion Timmermann when selecting the coding questions of the SGIC used by the EERG at TUHH. The criteria are divided into ones that *must* be fulfilled and ones that *should* be fulfilled. For each criterium, a negative example is given.

Each SGIC item must...

- ... apply to every participant; e. g. not "name of first pet", as not everyone has had a pet.
- ... be well known by the participant (Schnell et al., 2010; Damrosch, 1986; Hogben et al., 1948) but not by the researchers (Damrosch, 1986); e. g. not "blood type", as not everyone knows their blood type.
- ... not change over time (McGloin et al., 1996; Kearney et al., 1984; Damrosch, 1986; Hogben et al., 1948); e. g. not "number of siblings", as the parents may have another child in the future or a sibling dies.

SGIC items should...

- ... be uniquely identifiable (Hogben et al., 1948); e. g. not "hair color" as hair colors are on a spectrum with no objective partitions. Participants who have dyed their hair might also be confused which color to pick.
- ... be an unobservable attribute of the person (Damrosch, 1986); e. g. not "sex", especially in small groups.
- ... be something participants are willing to disclose; e. g. not "PIN code of mobile phone", as a participant might not want to disclose this information.
- ... have a high variation (McGloin et al., 1996; Kearney et al., 1984) within the group so it is helpful in discriminating; e. g. not "current academic affiliation", when the participants are currently all enrolled in the same university.

... be simple to state and understand; e. g. not "fifth letter in your mother's maiden name or last letter, if name consists of less than five letters". This criterium is important to avoid sampling bias (Grube et al., 1989; Kearney et al., 1984). Not only the participants with high cognitive ability should be able to answer consistently.

When interpreted strictly, there likely is not a single coding question that satisfies all theses criteria. Thus, in practice, the goal is to identify a set of coding questions that satisfy the criteria *well enough*, with the *must*-criteria being more important than the *should*-criteria.

Many of these criteria are difficult or impossible to quantify. However, there are two statistical quantities, the so-called u-*probability* and m-*probability* that can be used to quantify a combination of several of these criteria (Schnell et al., 2010). The u-probability is the probability that two different persons in a cohort give the same answer to a coding question. The m-probability is the probability that the same person gives the same answer to a coding question at different points in time. Ideally, the u-probability is 0 and the m-probability is 1. These probabilities are discussed in detail in the next section.

Schnell et al. (2010) provide u- and m-probabilities for many coding questions for the context of German university students. Based on their data, as well as a thorough discussion of the criteria listed above, a set of coding questions was decided upon, that has been used by the EERG at TUHH since 2015. It is depicted in Figure 6.1. The questions were selected to minimize the u-probabilities, while still fulfilling the criteria listed above as well as possible.

The first three coding questions (mother's name, day of birth, and father's name) were obvious choices based on the u- and m-probabilities measured by Schnell et al. (2010). Based on the list of criteria, these three questions likely are almost ideal, although there certainly are people who do not know their parents' names or their own birthday. The remaining four coding questions were compromises. The sixth question (place of birth) had very favorable u- and m-probabilities in the study by Schnell et al. However, many of the students at TUHH were born in the greater area of Hamburg, Germany. As shown in the next section, this large number of local students resulted in a lower u-probability for the place of birth. Still, due to it's high m-probability the question can still be considered good. The last coding question (year of birth) was included to allow the code to be used in long-term studies where university entry exams of many years are combined (Direnga et al., 2015, 2018). As the average response to this question would increase by 1 each year, the collision probability of the SGIC does not increase when data from another year is added to the data set. Together with the second coding question (day of birth), however, the code asks for two thirds of the students' birth date, information that is often available to instructors and peers. While this combination of questions reduces anonymity, the inclusion of both questions was considered the most viable option. The day of birth is one of the questions that best fits the listed criteria and the year of birth is the best solution for the large groups in long-term studies. The fourth and fifth question (number of brothers and sisters) were added as code collisions seemed too likely when only coding questions 1, 2, 3, 6, and 7 were used.

To allow easier reading of the codes, the questions are arranged so that the resulting code alternates between two letters and two numbers. While the set of coding questions stayed consistent, the phrasing of the questions was improved over time. The examples next to the questions (see Figure 6.1) were added later to prevent common misinterpretations. Initially, the questions for the number of brothers and sisters asked for two digit answers. These answers were changed to one digit, as the second digit was never used. Removing it emphasized that this question did not ask for the age of a sibling, an otherwise common mistake. For machine-read tests, a multiple choice version of the form is used.

6.1.2 u-*Probabilities of the Selected Coding-Questions*

As described above, the probability that two different participants give the same response to a coding question can be described statistically and usually is referred to as the u-probability (Schnell et al., 2010). The u-probability of each coding question can be determined empirically by comparing all the responses given to it in a single test. Since each student hands in only one answer sheet per test, all the answers collected in one test are from different students.

When $\mathcal{R}_k$ is the multiset[3] of responses to coding question k, the frequency that an individual in the population used response r for coding question k is

$$p(r,k) = \frac{|\mathcal{R}_k \cap \{r\}|}{|\mathcal{R}_k|}. \tag{6.1}$$

Assuming an infinitely large population with a distribution of responses as described by $p(r,k)$, the probability that two random individuals from that population use response r for question k is $p(r,k)^2$.

The u-probability u_k for question k is then calculated by summing up the probabilities for all responses as

$$u_k = \sum_{r \in \mathcal{U}_k} p(r,k)^2 = \sum_{r \in \mathcal{U}_k} \left(\frac{|\mathcal{R}_k \cap \{r\}|}{|\mathcal{R}_k|} \right)^2, \tag{6.2}$$

with $\mathcal{U}_k$ being the set of unique responses in $\mathcal{R}_k$.

3 a set which can contain identical elements

Table 6.1: u-probabilities for the coding questions used at TUHH. Compared are the responses from five different cohorts, their average, and literature data.

		u-Probability u_k						
k	Coding Question	ME1516 N = 632	ME1617 N = 609	EE1516 N = 275	CS1516 N = 124	CS1617 N = 111	Average N = 1751	Literature [a]
1	Mother's first name	2.2 %	2.3 %	2.6 %	3.1 %	3.4 %	2.5 %	3 %
2	Day of birth	3.4 %	3.3 %	3.5 %	3.5 %	4.6 %	3.5 %	3 %
3	Father's first name	1.9 %	1.9 %	2 %	2.6 %	2.7 %	2.0 %	2 %
-	Older siblings	36.6 % [b]	39.3 % [b]	36.6 % [b]	40.4 %	35.7 % [b]	38.7 %	36 %
4	Older brothers	53.4 %	63.6 %	49.7 %	*n/a*	54.4 %	57.9 %	*n/a*
5	Older sisters	53.4 %	52.4 %	55.5 %	*n/a*	52.3 %	54.9 %	*n/a*
6	Place of birth	18.2 %	14.2 %	13.7 %	15.0 %	11.9 %	15.5 %	2 %
7	Year of birth	19.8 %	21.4 %	18.9 %	*n/a*	14.4 %	19.9 %	*n/a*

a Literature data from Schnell et al. (2010) based on students in courses at four German universities.
b Calculated as the sum of the responses to coding questions 4 and 5.

To validate the choice of coding questions shown in Figure 6.1, students' identification codes in five representative cohorts were analyzed: Cohorts ME1516 and ME1617 consisted of students taking part in a first semester statics course at TUHH in winter 2015/16 and 2016/17. The cohort EE1516 consisted of students in the course EE1ME in the winter semester 2015/16. The cohorts CS1516 and CS1617 consisted of students taking part in a first semester computer sciences course at Hamburg University of Applied Sciences. Based on pretests conducted in these courses, the u-probabilities for all seven coding questions were calculated. The respective values are shown in Table 6.1[4]. The cohorts were selected so that there practically is no overlap in students.[5]

Table 6.1 also lists data from Schnell et al. (2010). For coding questions 1 through 5 as well as 7, the u-probabilities collected at TUHH are very similar to those reported by Schnell et al. This similarity is not surprising as Schnell et al. also collected their data at German universities. In contrast, the u-probabilities of coding question 6 (place of birth) are much higher than those reported by Schnell et al. This high u-probability is due to a large fraction of students at TUHH and Hamburg University of Applied Sciences being born in Hamburg. In the five cohorts investigated here, the fraction of students that selected `HA`

4 For this analysis, responses were considered identical when their distance was $d_k = 0$. d_k is defined in Section 6.1.3.

5 A group of no more than 60 Naval Architecture students were likely part of the cohorts ME1516 and EE1516. Their responses to the coding questions were recorded twice. Still, the effect of these duplicate responses is negligible, as the u-probabilities were calculated separately for each cohort.

as their place of birth was between 32% (CS1617) and 42% (ME1516). Large fractions strongly influence the u-probability.

While it is easy to collect data for the u-probabilities, data on the m-probabilities can only be collected with dedicated studies. To collect such data, the same student has to be asked the same coding question at multiple points in time. To provide statistically reliable results, hundreds of students would have to be reliably identified at multiple points in time. Since no suitable method of identification was available, the m-probabilities were not measured.

6.1.3 *Distances between Responses and Codes*

The decision whether two identification codes are matched is based on their similarity. This similarity is quantified by their distance d. For a code consisting of k coding questions, d is calculated as the sum of d_k, the distances of the responses to the coding questions: $d = \sum_k d_k$. Two responses to a coding question are either considered identical or different, resulting in a binary distance $d_k \in \{0, 1\}$. When determining if two responses are identical, three types of coding questions are distinguished based on the type of response they require:

TEXT QUESTIONS ask for letters. Two responses have a distance of $d_k{=}0$ if they are identical at every position and do not contain any blanks ([ ]). Otherwise, the responses have a distance of $d_k{=}1$. For all comparisons, capitalization is ignored, i. e. [a] is treated as an [A]. Also, umlauts (Ä, Ü, and Ö) are treated as non-umlauts, i. e. [Ä] is treated as [A].
Consequently, [ä][X] has a distance of $d_k{=}0$ from [A][X], and [ ][X] has a distance of $d_k{=}1$ from [ ][X].

NUMBER QUESTIONS ask for a number that is not part of a date. Leading blank fields are assumed to be zero. Two responses have a distance of $d_k{=}0$ if both are identical at every position and do not contain any blanks ([ ]) in non-leading fields. Otherwise, the responses have a distance of $d_k{=}1$. Consequently, [ ][3] has a distance of $d_k{=}0$ from [0][3] and [ ] has a distance of $d_k{=}0$ from [0], but [3][ ] has a distance of $d_k{=}1$ from [3][0].

DATE QUESTIONS ask for a number that is part of a date. Leading blank fields are assumed to be zero. Two responses have a distance of $d_k{=}0$ if both are identical at every position and do not contain any blanks ([ ]) in non-leading fields. Otherwise, the responses have a distance of $d_k{=}1$. Completely blank responses, however, are never considered a match. Consequently, [ ][3] has a distance of $d_k{=}0$ from [0][3], but [3][ ] has a distance of $d_k{=}1$ from [3][0]. Also, [ ][ ] has a distance of $d_k{=}1$ from [ ][ ] and [ ][0].

With text questions, the case of the letters is ignored as students' answers were inconsistent in that regard and the case usually does not contain any information. German umlauts (Ä, Ü, and Ö) were sometimes difficult to distinguish from non-umlaut characters (A, U, and O) as the dots of the umlauts sometimes came very close to or overlapped the bounding boxes in which the letters were supposed to be written. To prevent errors due to an umlaut incorrectly being read as a non-umlaut, umlauts are interpreted as non-umlauts. While this interpretation of umlauts slightly reduces the variation in answers and thus increases the u-probability, the reduced probability of errors when reading the umlauts was considered more important.

Analyzing students' responses to the coding questions on the number of siblings, it became clear that students frequently left empty the response-fields when the answer was zero and also often did not write leading zeros, especially when the question for number of brothers and sisters had asked for two digits unlike the example shown in Figure 6.1. A student would for example respond with [ ][ ] older brothers and [ ][1] older sisters. It is much more likely that this student meant that they had no older brother and one older sister instead of refusing to answer on the number of older brothers and incompletely stating the number of older sisters. Due to this answering behavior, number questions assume blank leading fields to be zero and even treat completely blank responses to be zero.

This handling of completely blank responses meant that students who did not answer any of the coding questions were considered to have answered that they had 0 brothers and 0 sisters. But, as only 2 of the 7 coding questions are number questions, completely blank responses would never be matched with each other.

With the questions of day of birth and the last two digits of the year of birth, completely blank answers were much less common. The day of the month (day of birth) can never be zero and it was considered unlikely that students born in 2000 would reply [ ][ ] as their year of birth instead of [0][0]. To prevent completely blank responses to these questions from being considered identical, completely blank responses to date questions are not treated as [0][0].

A more complex definition for d_k with values other than 0 and 1 would have been possible. The probabilities u_k and m_k could for example be taken into account when determining d_k. However, such approaches would have increased the complexity without a known benefit. Other methods for the calculation of the distance d are also possible, as for example described by Schnell et al. (2010). The approach described above, however, seemed to be sufficiently precise.

The multiset[a] of all pre-test codes is denoted by $\mathcal{A}$ and the multiset[a] of all post-test codes is denoted by $\mathcal{O}$. The distance between two codes $a \in \mathcal{A}$ and $o \in \mathcal{O}$ is denoted by $d_{a,o}$. The maximum distance between two matched codes $d_{max} \in \mathbb{N}_0$ is a set parameter. The algorithm consists of the following three steps, which are repeated as necessary:

1. All test pairs (a, o) with $a \in \mathcal{A}$ and $o \in \mathcal{O}$, for which the following three conditions apply, are matched:
   a) $\forall\, i \in \mathcal{A}, i \neq a : d_{a,o} < d_{i,o}$, i. e. post-test o is closer to pre-test a than to any other pre-test.
   b) $\forall\, i \in \mathcal{O}, i \neq o : d_{a,o} < d_{a,i}$, i. e. pre-test a is closer to post-test o than to any other post-test.
   c) $d_{a,o} \leqslant d_{max}$, i. e. the distance between a and o is less than or equal to the maximum allowed distance.
2. For each matched pair (a, o) a is removed from $\mathcal{A}$ and o from $\mathcal{O}$.
3. If at least one pair was matched, repeat the process starting with step 1.

a A set that can contain multiple identical elements.

Figure 6.2: The matching-algorithm used for SGICs.

6.1.4 *The Matching Algorithm*

The matching algorithm is designed to allow for exact as well as 1-off, 2-off, and in general n-off matching. This behavior is determined by the parameter d_{max}, which indicates the maximum distance between two matched codes. $d_{max}=0$ results in exact matching. In addition to d_{max}, the algorithm requires a table of the distances between all pre-test and post-test codes that are to be matched. An example for such a table is shown in Table 6.2a. The values for each field in such a table have to be calculated independently of each other as they are not related directly. For ease of reading, similar identification codes in this example are located near the main diagonal of the table.

The algorithm was designed to prioritize matching certainty over matching rate. In ambiguous cases where for example a pre-test code is an equally good match to two or more post-test codes, the pre-test will not be matched, even if the distance between the codes were below d_{max}.

An abstract description of the algorithm is shown in Figure 6.2. Step 1 of the algorithm identifies all matches in the current dataset. Steps 2 and 3 implement the iteration described later.

Table 6.2: Example of identification codes and their distances to illustrate the SGIC matching algorithm.

(a) Iteration 1, original table

Post-test \ Pre-test	BI 18 JA 00 HA 99	HA 18 JA 00 HA 98	AN 02 KL 11 LI 82	SA 12 UL 01 RE 97	KI 22 ST 00 LE 96
BI 18 JA 00 HA 98	1	1	7	6	5
HA 18 JA 00 HA 98	1	0	7	6	5
AN 02 KL 11 LI 96	7	7	1	6	6
AN 02 KL 11 LI 92	7	7	1	6	6
SA 12 UL 27 RE 97	5	5	7	2	7

(b) Single best match for each post-test (row) marked blue.

1	1	7	6	5
1	**0**	7	6	5
7	7	**1**	6	6
7	7	**1**	6	6
5	5	7	**2**	7

(c) Single best match for each pre-test (column) marked blue.

1	1	7	6	5
1	**0**	7	6	5
7	7	1	6	6
7	7	1	6	6
5	5	7	**2**	7

(d) Code pairs with a distance less than or equal to d_{max} marked blue.

1	**1**	7	6	5
1	**0**	7	6	5
7	7	**1**	6	6
7	7	**1**	6	6
5	5	7	2	7

(e) Iteration 2, reduced dataset.

Post-test \ Pre-test	BI 18 JA 00 HA 99	AN 02 KL 11 LI 82	SA 12 UL 01 RE 97	KI 22 ST 00 LE 96
BI 18 JA 00 HA 98	1	7	6	5
AN 02 KL 11 LI 96	7	1	6	6
AN 02 KL 11 LI 92	7	1	6	6
SA 12 UL 27 RE 97	5	7	2	7

(f) Iteration 3, reduced dataset.

Post-test \ Pre-test	AN 02 KL 11 LI 82	SA 12 UL 01 RE 97	KI 22 ST 00 LE 96
AN 02 KL 11 LI 96	1	6	6
AN 02 KL 11 LI 92	1	6	6
SA 12 UL 27 RE 97	7	2	7

In step 1, a pair of codes is considered a match, if it fulfills three criteria, which will be illustrated using the sample codes in Table 6.2a. In this example, 1-off matching is used, i. e. $d_{max}=1$.

Firstly, for each post-test (row) the best matching pre-test (column) is marked, as shown by the cells highlighted in blue in Table 6.2b. If two codes are an equally good match, neither is marked as can be seen in row 1. The distance of the best matching pre-test (column) can be larger than d_{max} as shown in row 5. Secondly, for each pre-test (column) the best matching post-test (row) is marked as shown by the cells highlighted in blue in Table 6.2c. As can be seen in rows 3 and 4, the best matches for the rows and columns are not necessarily the same. Thirdly, all cells with a distance less than or equal to d_{max} are marked, as shown by the cells highlighted in blue in Table 6.2d. Cells that fulfill all three criteria, i. e. where marked in all three tests, indicate a match.

The algorithm operates in an iterative manner. The matches found in step 1 are removed from the dataset in step 2. Step 3 tests if an iteration is necessary. If at least one match was found, the algorithm will go back to step 1, now using the reduced dataset. With $d_{max} > 0$, this iterative approach is required as codes can "block" each other from being matched.

When the algorithm is applied to Table 6.2a, it matches the codes beginning with `HA`. The codes beginning with `BI` are not matched as they also have a distance of 1 to the codes beginning with `HA`. After the codes beginning with `HA` have been removed from the dataset (step 2), the algorithm iterates again (step 3) as at least one match was found. The algorithm starts again with step 1, now in the reduced dataset shown in Table 6.2e. In the new iteration, the codes beginning with `BI` fulfill the matching criteria as the codes beginning with `HA` have been removed. The codes beginning with `SA` are not matched as, again, their distance is larger than d_{max}. Consequently, only row 1 and column 1 are removed from the dataset. Since at least one match was found, the algorithm iterates again, this time on Table 6.2f. Since no match is found in this iteration, the algorithm stops.

With $d_{max}=1$, the codes beginning with `BI` were considered a match, but only after the codes beginning with `HA` were removed from the dataset. The codes beginning with `HA` blocked the codes beginning with `BI` from being matched.

6.1.5 *Selection of* d_{max} *and Matching Rate*

When using the algorithm described above, an appropriate value for d_{max} has to be selected. $d_{max}=0$ will result in exact matching, while larger values of d_{max} will result in 1-off matching, 2-off matching, etc. Thus, a larger d_{max} can result in an increased matching rate, but will also increase the likelihood of collisions, i. e. false positive

Table 6.3: Matching and collision rates with different d_{max}. Matching rates (a) are based on real identification codes, collision rates (b) are based on Monte-Carlo simulation of randomly generated identification codes with the same distribution of responses as in (a) and 3000 iterations. The data for the groups ME, EE, and CS was averaged over two years. A plot of the data is shown in Figure 6.3 at right.

(a) Matching rates based on real identification codes and varying d_{max}.

			Matching Rate							
Grp.	N_{pre}	N_{post}	$d_{max}=0$	$d_{max}=1$	$d_{max}=2$	$d_{max}=3$	$d_{max}=4$	$d_{max}=5$	$d_{max}=6$	$d_{max}=7$
ideal	596	542	83.4 %	92.3 %	93.7 %	94.5 %	94.6 %	94.6 %	94.6 %	94.6 %
ME	632 + 609	401 + 287	64.5 %	78.8 %	83.1 %	85.6 %	85.8 %	85.8 %	85.8 %	85.8 %
EE	275 + 286	200 + 190	56.4 %	74.1 %	76.9 %	80.3 %	80.8 %	80.8 %	80.8 %	80.8 %
CS	124 + 111	114 + 87	44.3 %	63.7 %	69.2 %	69.2 %	69.7 %	69.7 %	69.7 %	69.7 %

(b) Collision rates based on randomly generated SGICs and varying d_{max}.

			Collision Rate							
Grp.	N_{pre}	N_{post}	$d_{max}=0$	$d_{max}=1$	$d_{max}=2$	$d_{max}=3$	$d_{max}=4$	$d_{max}=5$	$d_{max}=6$	$d_{max}=7$
ideal	596	542	6.52×10^{-5}	0.8 %	7.7 %	9.9 %	9.9 %	9.9 %	9.9 %	9.9 %
ME	632 + 609	401 + 287	5.54×10^{-5}	0.8 %	9.3 %	12.5 %	12.6 %	12.6 %	12.6 %	12.6 %
EE	275 + 286	200 + 190	2.74×10^{-5}	0.4 %	7.5 %	12.8 %	12.9 %	12.9 %	12.9 %	12.9 %
CS	124 + 111	114 + 87	1.49×10^{-5}	0.2 %	5.1 %	12.6 %	12.9 %	12.9 %	12.9 %	12.9 %

matches. Like many other research groups (see e. g. Kearney et al., 1984; Grube et al., 1989; Faden et al., 2004), the EERG decided to use 1-off matching, i. e. $d_{max}=1$. This decision was substantiated through an analysis using a representative dataset.

The dataset consisted of pre- and post-test identification codes of seven cohorts. These cohorts were divided into four groups. The sizes of the groups and cohorts are listed in Table 6.3. The group called "ideal" consisted of one cohort of second semester Mechanical Engineering students whose pre- and post-tests were conducted in the same lecture setting, 45 minutes apart. Thus, the same students participated in both tests, except for possibly a few of students who left early or came late. The pre-test used a multiple-choice version of the identification code, while the post-test used a hand-written version similar to the one shown in Figure 6.1. The group ME consisted of the cohorts ME1516 and ME1617, introduced in Section 6.1.2. The group EE consisted of the cohort EE1516, also described in Section 6.1.2, as well as the cohort EE1617 one year later. The group CS consisted of the cohorts CS1516 and CC1617 also introduced in Section 6.1.2. While in the group EE the pre- and post-test were 3 weeks apart, the pre- and post-tests of the groups ME and CS were given at the beginning and end of the semesters, respectively. They were about 14 weeks apart.

The decision for the ideal d_{max} can be illustrated using Figure 6.3. The horizontal axis of that figure represents different values for d_{max}, the vertical axis compares the matching and collision rate for the four groups. Data for each group is indicated by a differently shaped and colored marker. Markers that are filled indicate data for the matching rate, markers that are not filled indicate data for the collision rate. Desired is a high matching rate and a low collision rate, i. e. a large distance between the markers at the top and the markers at the bottom of the figure. The data points shown in Figure 6.3 are listed in Table 6.3.

The matching rate of each group is the average of the matching rates of the cohorts the group consists of. The matching rate for each cohort was calculated by simply running the algorithm described in Section 6.1.4 for all possible values of d_{max} (0 to 7). The fraction of post-tests that were matched is the matching rate.

The collision rate of each group is the average of the collision rates of the cohorts that the group consists of. As described in the introduction of this section, the collision rate of a cohort is the fraction of post-tests of that cohort that were incorrectly matched to a pre-test. Such an incorrect match can occur when different students have the same SGIC, or when they have similar SGICs and non-exact matching is used. Without being able to unambiguously identify the students in each cohort, the collision rate cannot be calculated directly. However, it can be estimated using randomly generated identification codes. For each cohort, the frequency of each response to each coding question is known. Based on the distribution of these responses to the coding questions, N_{pre} pre- and N_{post} post-test identification codes can be generated randomly. These represent $N_{pre} + N_{post}$ different students. The fraction of these post-test identification codes that are matched to a pre-test identification code can be considered the collision rate of the cohort. As a collision rate calculated this way is heavily dependent on the randomly generated identification codes, a Monte-Carlo simulation[6] was used. The calculation described above was repeated 3000 times. The collision rates for all iterations were averaged. After 3000 iterations, the values shown in Table 6.3b had stabilized and did not change when number of iterations was increased.

The matching rates of each group in Figure 6.3 strongly increases from $d_{max}=0$ to $d_{max}=1$. The increase is much less from $d_{max}=1$ to $d_{max}=2$ and virtually zero for higher values of d_{max}. In contrast, the percentage of collisions stays at or close to zero up to $d_{max}=1$ and only increases afterwards. Thus, with $d_{max}=1$ there is a significantly increased matching rate with the collisions still below 1%. Because of this difference, $d_{max}=1$ is used for matching by the EERG at TUHH.

6 A Monte-Carlo simulation is understood here as a simulation to determine the behavior of a deterministic system using randomly sampled input data. The simulation is repeated for a large number of input data and the results are averaged.

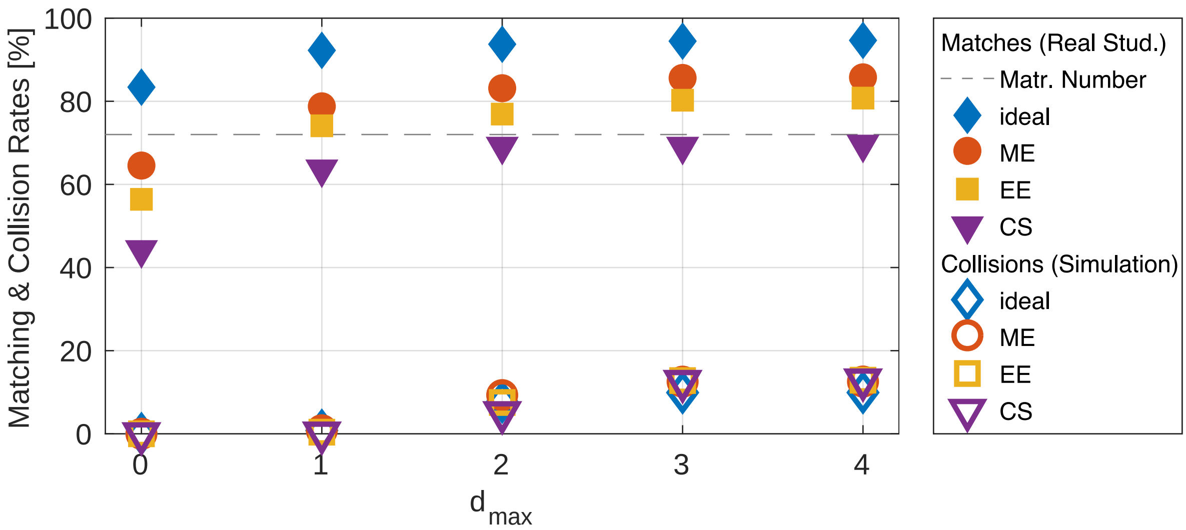


Figure 6.3: Matching and collision rates with different d_{max}. Cohort sizes and exact percentages can be found in Table 6.3.

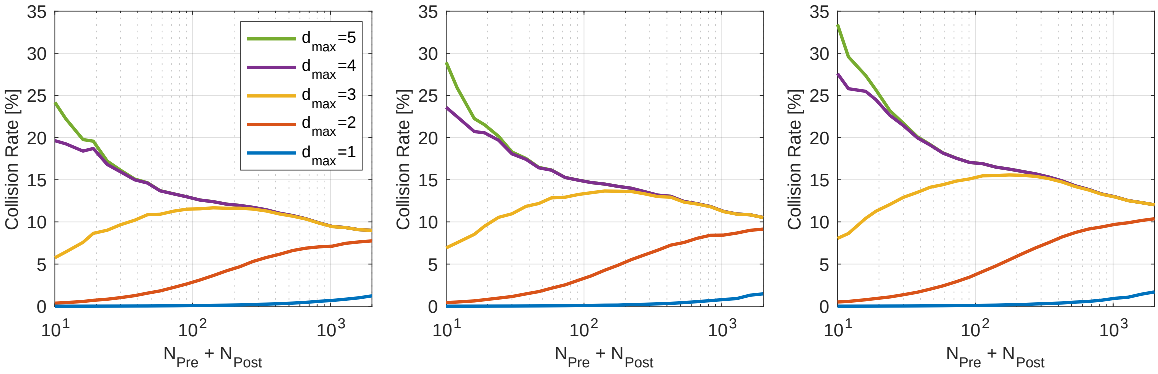
The matching rate with SGICs and $d_{max}=1$ is higher than the matching rate achieved with matriculation numbers in standardized tests up to 2015, as can be seen in Figure 6.3. The lower number of blank or obviously fake identification codes also indicates a higher acceptance by students.

It is likely that the collision rate with real data is even less than the values shown in Table 6.3. As can be seen in that table, most of the collisions with $d_{max}=1$ are not exact, but 1-off matches. Real datasets, however, contain mostly exact matches. In the first iteration of the matching algorithm these exact matches are removed from the dataset, leaving a much smaller dataset for the non-exact collisions.

6.1.6 *Collision Rates for Large Cohorts*

The data shown in Table 6.3 can be used to estimate the collision rate in cohorts similar to those shown in the table. The collision rates for the cohorts EE1516 and EE1617 can for example be used to estimate the collision rates in other cohorts of the course EE1ME when these have similar numbers of students. Such an estimate is not possible for cohorts that are not similar to those in the dataset, especially ones with significantly different numbers of students.

Figure 6.4 provides an overview of collision rates for different d_{max}, ratios of pre- and post-tests, and number of tests overall. It is based on a Monte-Carlo simulation that used randomly generated identification codes, based on the responses of all cohorts shown in Table 6.1. The simulation was repeated until each data point was based on at least $1.8 \cdot 10^8$ tests. It can clearly be seen that $d_{max}>1$ will lead to a



(a) $N_{pre}/N_{post} = 1/1$ (b) $N_{pre}/N_{post} = 7/5$ (c) $N_{pre}/N_{post} = 2/1$

Figure 6.4: Collision rate vs. number of tests for different d_{max} and ratios of pre- and post-tests. This data is based on a Monte-Carlo simulation. Each data point is based on at least $1.8 \cdot 10^8$ tests.

significant number of collisions. The number of collisions for $d_{max}=1$ stays below 2% for up to 2000 tests.

6.1.7 *Estimation of Collision Rates*

Calculations as the ones shown in Figure 6.4 are very time-consuming. When designing a SGIC, different numbers and combinations of coding questions need to be compared and their collision rates estimated. For such cases, it would be beneficial to be able to directly calculate the probability of collisions. First steps to develop an algorithm for such a calculation are presented below.

First, p_d, the probability that two random identification codes have a distance of d, can be calculated based on the u-probabilities. The algorithm for this calculation is shown in Figure 6.5. The "Algorithm" column of Table 6.4 shows the values for p_d that were calculated using the average u_k in Table 6.1.

To verify the algorithm for p_d, values for p_d can also be calculated directly using the distances of all identification codes in a test. Table 6.4 lists the directly calculated p_d for all tests of the cohorts ME1516, ME1617, and EE1516. Their average p_d is also tabled.

Comparing the "Average" and "Algorithm" columns, it can be seen that the algorithm produces realistic results. The remaining differences can be explained by two effects. Firstly, the values in the "Algorithm" column were calculated based on the average u_k in Table 6.1, which also included the cohorts CS1516 and CS1617. Secondly, the algorithm ignores possible correlations between individual responses, like possible correlations between a participant's year of birth and the first names of their parents. The p_d from the direct calculation shows that no two students in the three cohorts had the

For a SGIC with n coding questions and the u-probabilities u_k:

1. $\mathcal{X}$ is the set of all possible n-tuples consisting of only 0s and 1s. For $n = 2$:

$$\mathcal{X} = \{(0,0),\ (0,1),\ (1,0),\ (1,1)\}$$

2. For $x \in \mathcal{X}$, x_k is the kth number in the n-tupel x.

   $x_k = 0$ means that the kth answer of x has a distance of 0, i. e. it is a match. $x_k = 1$ means no match for this answer.

3. For $0 \leqslant d \leqslant n$, $\mathcal{X}_d$ is the subset of $\mathcal{X}$, that contains all n-tupels with exactly d zeros, i. e. all n-tupels that have d matching answers.

4. Now p_d can be calculated as

$$p_d = \sum_{x \in \mathcal{X}_d} \prod_{k=1}^{n} \begin{cases} 1 - u_k & \text{for } x_k = 1 \\ u_k & \text{for } x_k = 0 \end{cases} \qquad (6.3)$$

Figure 6.5: Algorithm to calculate p_d based on the u-probabilities of a SGIC with n coding questions.

same SGIC. This probability is non-zero for the values calculated by the algorithm.

In a second step, c_d, the probability that two random codes have a distance of d *or less*, as well as $\bar{c}_d$, the probability that two random codes have a distance of *more than* d, can then be calculated based on p_d:

$$c_d = \sum_{i=0}^{d} p_i \qquad \text{and} \qquad \bar{c}_d = 1 - c_d \qquad (6.4)$$

These probabilities can be combined to calculate $P_{d_{max}}(N_{pre}, N_{post})$, the probability that a pair of random identification codes is considered a match, based on d_{max}, N_{pre}, and N_{post}:

$$P_{d_{max}}(N_{pre}, N_{post}) = \sum_{d=0}^{d_{max}} p_d \cdot \bar{c}_d^{\,N_{pre}+N_{post}-2} \qquad (6.5)$$

For a code pair to be matched with a distance of 0, this code pair must have a distance of zero, which occurs with a probability of p_0. All other $N_{pre} + N_{post} - 2$ distances in the same row and column of the matching table (see Table 6.2), have to be larger than 0, which occurs with a probability of $\bar{c}_0$. If d_{max} is larger than 0, the probabilities of a match with these higher distances have to be added.

Table 6.4: Probabilities that two different individuals have a code with distance d. Data in ME1516, ME1617, and EE1516 columns as well as their average was calculated directly. The data in the "Algorithm" column was calculated using the algorithm presented in Figure 6.5 and the average u_k shown in Table 6.1.

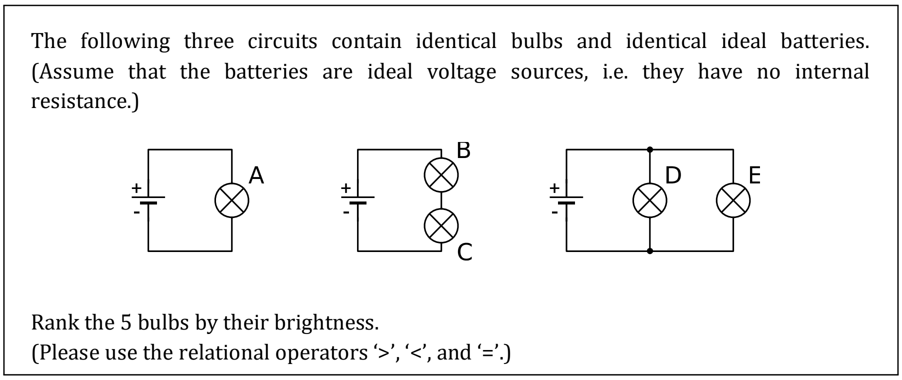
d	Collision Probability p_d				
	ME1516 N = 632	ME1617 N = 609	EE1516 N = 275	Average	Algorithm
0	0	0	0	0	1.73×10^{-7}
1	2.65×10^{-5}	1.00×10^{-5}	2.16×10^{-5}	1.77×10^{-5}	2.18×10^{-5}
2	9.56×10^{-4}	1.29×10^{-3}	1.19×10^{-3}	1.19×10^{-3}	9.71×10^{-4}
3	1.89×10^{-2}	2.28×10^{-2}	2.04×10^{-2}	2.12×10^{-2}	1.80×10^{-2}
4	1.16×10^{-1}	1.40×10^{-1}	1.28×10^{-1}	1.31×10^{-1}	1.28×10^{-1}
5	3.57×10^{-1}	3.50×10^{-1}	3.69×10^{-1}	3.59×10^{-1}	3.66×10^{-1}
6	3.59×10^{-1}	3.52×10^{-1}	3.62×10^{-1}	3.57×10^{-1}	3.68×10^{-1}
7	1.48×10^{-1}	1.33×10^{-1}	1.19×10^{-1}	1.30×10^{-1}	1.19×10^{-1}

However, this calculation assumes the distances in the matching table are random, which is not the case in reality. The distances are based on the identification codes of the respective row and column in the matching table. The calculation also only models step 1 of the matching algorithm, but not the iterations in steps 2 and 3. These steps are difficult to incorporate in a closed equation. Still, the probabilities introduced above can likely be used to approximate the functions shown in Table 6.4. However, such an approximation is beyond the scope of this thesis.

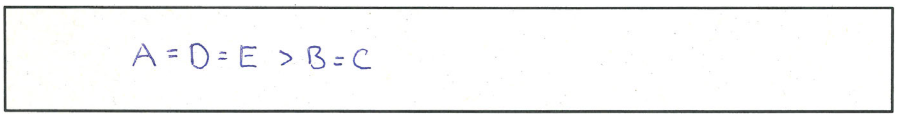
6.1.8 *Summary*

This section introduced SGICs, which are used by the EERG at TUHH since 2015 to identify tests answered by the same student. As shown in Section 6.1.5, SGICs provide a higher matching rate than the matriculation numbers used before. In this thesis, the SGICs will be used in Section 9.6 to determine which students in the post-test analyzed there had also participated in the Tutorial *Potential* and to track the change of beliefs of individual students.

The coding questions and matching algorithm presented here can also be used in other research projects. The collision rates are projected for different sizes of cohorts and ratios of pre- and post-tests so that the feasibility of SGICs can be estimated before their use.



(a) The question as given to students.



(b) Correct answer in the most common format.

(c) Correct answer in an uncommon format.

Figure 6.6: The five-bulbs test and different answers by students.

6.2 ALGORITHMIC ANALYSIS OF RANKING QUESTIONS

As described in Section 5.3.4, ranking questions such as the five-bulbs test shown in Figure 6.6 are a valuable tool to investigate student understanding. These qualitative questions allow to compactly ask for the *relation* between many *quantities* at once. By asking students to not simply order the quantities, but to rank them using relational operators, the answers encode the relation between every quantity in the ranking, not only the quantities connected directly by a relation.

For instance, the answer shown in Figure 6.6b explicitly states that A=D, D=E, E>B, and B=C. Yet, through the relational operators, the answer also contains the relations A=E, A>B, and A>C, as well as the relation for each remaining pair of the five quantities. These relations could not be determined if a student simply ordered the bulbs by their brightness, as e.g. A, D, E, B, C. With the simple ordering it is not clear if two quantities are equal or different. Thus, it is not possible to determine from such an ordering if a student believes current to be "used up" (B≠C) or not (B=C). In fact, such orderings allow students to hide their uncertainty. If a student knows bulbs D and E as well as B and C are equally or similarly bright and that A is at least as bright as D and E, they can order the bulbs as A, D, E, B, C without committing to any specifics.

The drawback of ranking questions is their large number of possible answers. While most students tend to write their answer as one closed statement with the largest quantity at left and the smallest quantity at right (see Figure 6.6b), there almost always also are students who do not use this formatting. They might simply start with the smallest quantity at left, but might also list several individual statements, as shown in Figure 6.6c.

While it helps to transcribe these answers to a uniform format, checking rankings for specific relations (e. g. $A>B$ and $A>C$) still requires considerable effort, as each unique ranking has to be analyzed individually. Additionally, it can be difficult to identify contradictions in a ranking. In the ranking in Figure 6.6c, for example, one cannot see immediately if the ranking is free of contradictions. To reduce the time required to evaluate ranking questions, to ensure no contradictions are missed, and to allow ranking questions to be used in automatically graded online quizzes, a software solution is needed. Since no suitable algorithm was found in literature[7], one was developed and is documented in the following.

Most ranking tasks are designed so that students must only use the relations '$>$', '$=$', and '$<$', but not the relations '$\geqslant$' and '$\leqslant$'. At TUHH ranking tasks explicitly told students to use the relational operators '$>$', '$=$', and '$<$'. Still, some students also used the operators '$\geqslant$' and '$\leqslant$'. The relation '$\geqslant$' is less precise than '$>$' and '$=$'. Thus, the ranking $X \geqslant Y$ is not considered identical to the ranking $X>Y$ as it does not exclude $X=Y$. Still, the operators '$\geqslant$' and '$\leqslant$' can be part of correct rankings. When the correct ranking is $X>Y>Z$ and a student answers $X \geqslant Y>Z$, their answer regarding X and Z is correct.

In Section 6.2.1, the steps necessary to calculate the relation between any two quantities in a ranking will be described. To simplify the description, it is assumed that the relations in a ranking are consistent with each other. In Section 6.2.2, that assumption is dropped.

6.2.1 *Algorithm for Consistent Rankings*

The algorithm consists of three steps. First, a given ranking is translated into a graph. Second, the relations between all quantities are evaluated using this graph. Third, if more than one relation is to be evaluated, individual relations are collected in a relation table. The values of these can be compared using three-valued logic. For the following description, it is assumed that the given ranking does not contain any inconsistent relations. An example for a ranking with inconsistent relations would be $X>Y>Z>X$.

7 While general-purpose computer algebra systems, such as Maple and Mathematica, can be used to analyze systems of inequalities, their integration into the existing workflow for the evaluation of tests as well as their use in online quizzes seemed problematic at best.

6.2.1.1 *Construction of the Graph*

Firstly, the graph will be described using the examples shown in Figure 6.7. Secondly, the algorithm for its creation is presented.

Each of the quantities to be ranked is one node of the graph. The rankings shown in Figure 6.7 all contain the five quantities A, B, C, D, and E. Thus, each graph in Figure 6.7 also contains the five nodes A, B, C, D, and E. Each relation in a ranking ('>', '⩾', '=', '⩽', '<') is described by an arc, i. e. a directed edge, in the graph. The relations '>' and '⩾' are translated into arcs that point from the larger to the smaller quantity. The relation $E>B$ in Figure 6.7a, for example is translated into an arc labeled '>' that points from E to B. The relations '<' and '⩽' are "read backwards" and then treated as above. The relation $C<D$ in Figure 6.7d, for example, is read as $D>C$ and thus in the corresponding graph there is an arc labeled '>' from D to C. Equal relations are two arcs, pointing in opposite directions. Consequently, they can be treated as non-directional edges. For ease of reading, these arcs are represented by one arrow with two heads in the examples in Figure 6.7.

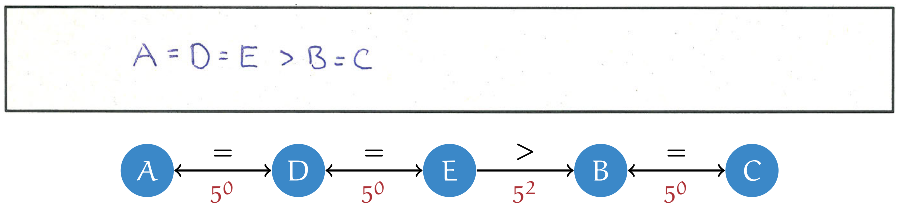
In Figure 6.7, the type of an arc is indicated by the arc's label, but also encoded in its weight. For '=' relations, this weight is the number of nodes to the power of 0, i. e. 5^0. For '⩾', it is the number of nodes to the power of 1, i. e. 5^1. For '>', it is the number of nodes to the power of 2, i. e. 5^2. This choice of the weights is explained in the next subsection.

The formal description of the algorithm to construct a graph from a given ranking is shown in Figure 6.8.

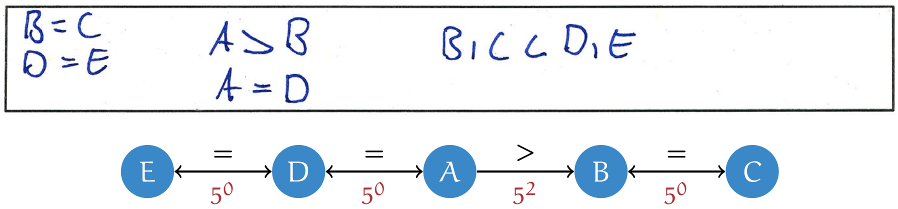
6.2.1.2 *Determining the Relations between all Quantities*

The relation between any two elements in a ranking can be determined by examining the arcs on the path between them in the graph. As can be seen in Figure 6.7, the rankings in Subfigures (a) and (b) are logically identical, but written differently. Similarly, the paths between the elements in the respective graphs contain the same types of arcs, but in a different quantity and order. While for example the shortest path from A to B in both graphs is different, both of these paths pass over an '>' arc, indicating that $A>B$. The shortest paths between A and E only pass over '=' arcs in Figures 6.7a and 6.7b, meaning that in both cases $A=E$. In Figure 6.7d, there is no (shortest) path from A to D. The ranking does not specify a relation between these two quantities.

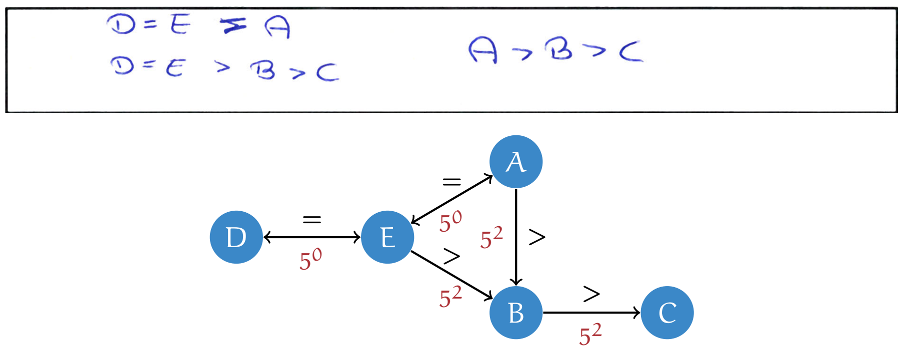
Since all '<' and '⩽' are read backwards, the graph only contains the three edge types '=', '⩾', and '>'. In the graph, these are represented by the arcs' weights. The weights are powers of the number of nodes. As the examples in Figure 6.7 all contain 5 nodes the weights are 5^0, 5^1, and 5^2. The weight of an arc encodes the relation between the



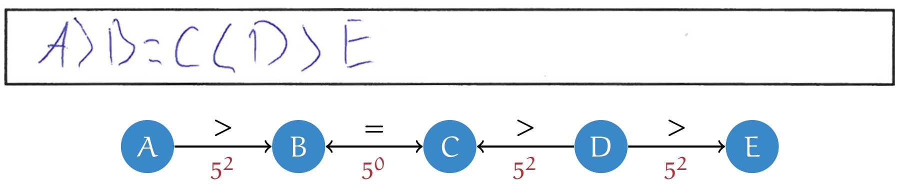
(a) Answer in the most common format, quantities ordered from largest to smallest.



(b) Unsorted, unconnected ranking. The ill-formed statement “B, C < D, E” has been ignored for the graph.



(c) Ranking with redundant information.



(d) Ranking with missing relations/paths. Note that C<D is represented by a ‘>’ arrow pointing form the right (D) to the left (C).

Figure 6.7: Examples of student rankings and their corresponding graphs. Note that rankings (a) and (b) are logically equivalent. Each arc is labeled with its edge type and its weight (red number), assuming 5 nodes. For simplicity, arcs for the equal relation (=) are shown as a single arrow with two heads.

The following will describe how to construct the graph G, which will represent a given ranking.

1. The set $\mathcal{T}$ contains all the types of relations the graph's edges can describe: $\mathcal{T} = \{`=', `\geqslant', `>'\}$. Note that this set does not contain the relations '<' and '⩽'.

2. The graph $G = (\mathcal{Q}, \mathcal{R})$ consists of $\mathcal{Q}$, the set of nodes, and $\mathcal{R}$, the set of directed arcs. Each node $Q \in \mathcal{Q}$ represents one quantity in the ranking. Each arc $R \in \mathcal{R}$ represents one relation in the ranking and is a 3-tuple, consisting of its start and end node, as well as the relation type:

$$\forall\, R \in \mathcal{R} : R = (A, B, T) \text{ with } A, B \in \mathcal{Q} \text{ and } T \in \mathcal{T}.$$

3. The relation ranking function t assigns each relation a number:

$$\begin{aligned} t : T &\to \mathbb{N}_0 \\ `=' &\mapsto 0 \\ `\geqslant' &\mapsto 1 \\ `>' &\mapsto 2 \end{aligned}$$

4. Using this function, each arc can be assigned a weight using the weighting function:

$$\begin{aligned} w : \mathcal{R} &\to \mathbb{N}_0 \\ R &\mapsto |\mathcal{Q}|^{t(T)}, \text{ with } R = (A, B, T). \end{aligned}$$

5. Using these definitions, each relation in a ranking can be converted into the graph G by ensuring that A and B are in $\mathcal{Q}$ and adding arcs depending on the relation between A and B:
   $A > B$: Add $(A, B, `>')$ to $\mathcal{R}$.
   $A \geqslant B$: Add $(A, B, `\geqslant')$ to $\mathcal{R}$.
   $A = B$: Add $(A, B, `=')$ and $(B, A, `=')$ to $\mathcal{R}$.
   $A \leqslant B$: Add $(B, A, `\geqslant')$ to $\mathcal{R}$.
   $A < B$: Add $(B, A, `>')$ to $\mathcal{R}$.

Figure 6.8: Algorithm to construct a graph from a ranking.

1. For the elements A and B, calculate the distance from A to B and the distance from B to A denoted by $d_{A,B}$ and $d_{B,A}$. Standard approaches like Dijkstra's algorithm (Cormen et al., 2009, p. 658) can be used to calculate these shortest paths.

2. Factorize $d_{A,B}$ in

$$d_{A,B} = \sum_{x \in \mathcal{T}} d_{A,B,x} \cdot |Q|^{t(x)} \tag{6.6}$$

   and $d_{B,A}$ in

$$d_{B,A} = \sum_{x \in \mathcal{T}} d_{B,A,x} \cdot |Q|^{t(x)}. \tag{6.7}$$

   $d_{A,B,'='}$ now indicates how many '=' are on the shortest path from A to B, $d_{A,B,'<'}$ now indicates how many '<' are on the shortest path from A to B, etc.

3. The relation between A and B is as follows:
   if $d_{A,B,'>'} > 0$: $A > B$, otherwise
   if $d_{A,B,'\geqslant'} > 0$: $A \geqslant B$, otherwise
   if $d_{B,A,'>'} > 0$: $A < B$, otherwise
   if $d_{B,A,'\geqslant'} > 0$: $A \leqslant B$, otherwise
   if $d_{A,B,'='} > 0$: $A = B$, otherwise
   no relation between A and B.

Figure 6.9: Algorithm to determine the relation between two quantities based on the graph of a ranking.

nodes it connects. Similarly, the length of a path, defined as sum of the weights of the arcs along that path, encodes the relation between the two nodes at each end of that path. A shortest path in a graph with n nodes can consist of no more than $n - 1$ arcs. Thus the length of each shortest path can be factorized unambiguously to determine how many arcs of each type are part of it.

Using this factorization, the relation between any two quantities in a ranking can be calculated using the ranking's graph and the algorithm presented in Figure 6.9. The calculations of the path lengths can be made using standard graph algorithms, like Dijkstra's algorithm (Cormen et al., 2009, p. 658).

If more than a single relation is to be tested, it is more economical to first determine the relations between all quantities in a ranking (see Cormen et al., 2009, Ch. 25). The algorithm described in Figure 6.9

Table 6.5: Relation tables for the rankings shown in Figure 6.7. The relations are read from left bottom to top right. The identity relation (≡) is used for pairs of quantities that are equal by definition. Question marks (?) are used to indicate relations that the ranking did not contain.

(a) For Figures 6.7a and 6.7b.

	A	B	C	D	E
A	≡	>	>	=	=
B	<	≡	=	<	<
C	<	=	≡	<	<
D	=	>	>	≡	=
E	=	>	>	=	≡

(b) For Figure 6.7d.

	A	B	C	D	E
A	≡	>	>	?	?
B	<	≡	=	<	?
C	<	=	≡	<	?
D	?	>	>	≡	>
E	?	?	?	<	≡

can be modified to determine the relations between all quantities in a graph at once. The results can be stored in relation tables like the ones shown in Table 6.5. If several different relations in a ranking need to be tested, it likely is faster to first calculate these tables for each student's ranking and then perform the tests by looking up the respective relations in the tables. The top right half of such a table is the logical negation of the bottom right.

Logically equivalent rankings result in identical relation tables. Consequently, these tables can be used to automatically determine and count the most common rankings for a question. To allow for such operations the tables should contain all quantities the task asked students to rank, not simply the quantities a student did rank.

6.2.1.3 *Evaluation of Specific Relations in a Ranking*

When evaluating a specific relation in a student's ranking, three different cases can be distinguished: (1) The relation in question is part of the student's ranking and stated correctly (see B=C in Figure 6.7d), (2) the relation in question is part of the student's ranking and stated incorrectly (see D>E in Figure 6.7d), and (3) the relation is not part of the student's ranking (see A=D in Figure 6.7d). When grading students' answers, cases (2) and (3) will likely both be treated as a false answer. However, when investigating student understanding, it can be of interest to differentiate how many students did not make a statement about a relation compared to those that incorrectly stated that relation. Thus, three cases must be differentiated: a (1) correct answer, (2) incorrect answer, and (3) no answer, or (1) *true*, (2) *false*, and (3) *unknown*.

Furthermore, it can be important to test not only one relation, but the logical combination of several relations. For example, the answers of the five-bulbs test (see Figure 6.6) could be analyzed to identify

A detailed analysis of the five-bulbs test is presented in Section 7.1 (p. 106).

Table 6.6: Truth tables for basic operators using three-valued logic with the values *true* (T), *false* (F), and *unknown* (?).

(a) AND

		B		
		F	?	T
A	F	F	F	F
	?	F	?	?
	T	F	?	T

(b) OR

		B		
		F	?	T
A	F	F	?	T
	?	?	?	T
	T	T	T	T

(c) NOT

A	$\bar{A}$
F	T
?	?
T	F

rankings that indicate the misconception of current being "used up". These rankings contain the relation $A{=}B{>}C$ or $A{=}C{>}B$ depending on the direction of current being considered. As one test, these relations can be written as ($A{=}B$ AND $B{>}C$) OR ($A{=}C$ AND $C{>}B$). Comparing the four conditions with the relations in Table 6.5a yields (*false* AND *false*) OR (*false* AND *false*), which is *false*. Thus, the respective student(s) likely did not believe current to be "used up".

The AND and OR operators in the statement above are not simple boolean operators. As the values on each of their sides can be *true*, *false*, and *unknown*, these operators must use the three-valued logic first described by Kleene (1938). Suitable truth tables for three-valued logic are shown in Table 6.6 for the operators AND, OR, and NOT.

6.2.2 *Extensions to the Algorithm to Treat Inconsistent Answers*

The description up to this point assumed that the relations in the rankings were consistent. This section presents modifications to the algorithm to test for possible inconsistencies. Three types of inconsistencies are distinguished. (1) inconsistent arcs, where two relations are defined for the same pair of quantities (e. g. a students ranks $A{>}B$ and $A{=}B$), (2) inconsistent cycles, where an element is not equal to itself (e. g. a student ranks $A{>}B{>}A$), and (3) inconsistent paths, where the relation between two elements is indirectly defined in an inconsistent way (e. g. a students ranks $X{\geqslant}Y_1{\geqslant}Z$ and $X{>}Y_2{>}Z$). The following three sections discuss each inconsistency in detail and describe approaches to detect them.

6.2.2.1 *Inconsistent Arcs*

Inconsistent arcs occur when there are multiple definitions for one particular relation, i. e. a student explicitly writes $A{>}B$ but also $A{=}B$. In the graph, such an inconsistency would result in two non-identical arcs between a pair of nodes. As many implementations of standard graph algorithms assume there to be only one arc between a pair of nodes, it is best to treat this inconsistency when constructing the graph from a ranking.

In the algorithm described in Figure 6.8, the set $\mathcal{T}$ can be extended to contain a special edge type used to indicate an inconsistent arc (‘↯’). If greater equal ($\geqslant$) and less equal ($\leqslant$) relations are allowed, it might even be necessary to further differentiate this special edge type to indicate which combination of relations it contains. The function t for the ordering of the edges has to be modified to always favor these special edge types, i. e. they must be assigned the lowest weight. In step 5, an additional check must be added. When an arc is to be added to the graph, it must first be tested if a different arc already exists between the nodes the new one is supposed to connect. If that is the case, the new arc is not added but the existing arc is changed to be an inconsistent arc (‘↯’).

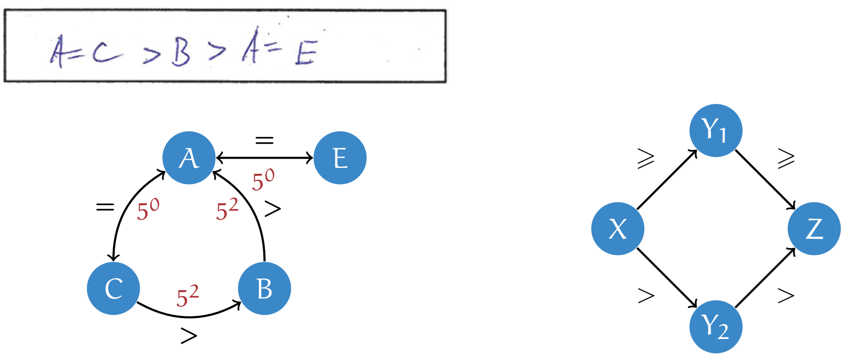
In step 3 of the algorithm described in Figure 6.9, it must be tested if $d_{A,B,\text{'↯'}}>0$ or $d_{B,A,\text{'↯'}}>0$. If that is the case, the relation between A and B is defined inconsistently and should be marked as such in the relation table.

Inconsistent arcs can be seen as a special case of inconsistent paths or inconsistent cycles. However, for the reasons described above, it is suggested to address them as described above.

6.2.2.2 *Inconsistent Cycles*

Inconsistent cycles likely are most common type of inconsistency. They can occur when a quantity is used twice in a ranking, as for example quantity A in Figure 6.10a. The ranking shown in the figure explicitly states that $A>A$, but looking at the graph the ranking also results in $B>B$, $C>C$, and since $E=A$ also in $E>E$.

These types of inconsistencies can be found in the graph by using strongly connected components, i. e. parts of the graph in which every node is reachable from every other node (Cormen et al., 2009, Sec. 22.5). Every strongly connected component of a graph that con-



(a) Conflicting cycle ($A > A$). (b) Conflicting paths.

Figure 6.10: Examples for graphs with inconsistent relations.

tains a relation that is not equal (=) is an inconsistent cycle. In the example shown in Figure 6.10a, the graph has one strongly connected component, which is the whole graph. Since this graph contains at least one edge that is not equal (=), the relations between all nodes in this strongly connected component (in this example the whole graph) are inconsistent and should be marked as such in the relation table.

6.2.2.3 *Inconsistent Paths*

An inconsistent path can only occur when a ranking contains not only the relations *greater* or *less* ($>/<$), but also the relations *greater-equal* or *less-equal* ($\geqslant/\leqslant$). Since the quizzes used in this thesis did not ask students to use the greater-equal or less-equal relations, this type of inconsistency was not observed in students' answers.

A theoretical example for an inconsistent path can be seen in Figure 6.10b. One path between X and Z passes over Y_1 and only uses greater-equal relations, meaning $X \geqslant Y_1 \geqslant Z$ and thus $X \geqslant Z$. The other path passes over Y_2 and only uses greater relations, i. e. $X > Y_2 > Z$ and thus $X > Z$. $X \geqslant Z$ and $X > Z$ are different statements about the relation between X and Z. While mathematically this statement could be interpreted favorably as $X > Z$, it is still considered as an inconsistency. The student made two different statements about the relation of these two quantities and it is not clear what the student's intentions were.

To detect such inconsistencies the algorithm has to be modified to not only search for the shortest path between two nodes, but also for the longest non-cyclic path between these two nodes. If the relation determined by the longest path is not identical to the relation determined by the shortest path, there is an inconsistent path between the two nodes. The longest non-cyclic path can be found by inverting the weights, e. g. by using $t : T \to \mathbb{N}$ with '$=$' $\mapsto 2$, '$\geqslant$' $\mapsto 1$, and '$>$' $\mapsto 0$, and then using the algorithm for finding the shortest path. If the shortest and longest path contain different edge types, an inconsistent path exists between the tested nodes.

6.2.3 *Conclusion*

The algorithm described above was implemented in Matlab and used to evaluate the ranking questions used in this thesis. It allowed for easy investigation of different relations in ranking questions. The algorithm can also be integrated in web-based self assessments.

7 STUDENT UNDERSTANDING OF CURRENT AND VOLTAGE

This chapter discusses different aspects of students' understanding of current and voltage, especially of Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL). It highlights student difficulties with these concepts and investigates the effectiveness of Tutorial worksheets in helping students overcome these difficulties. Thereby, the chapter will contribute to answering research questions RQ 1 and RQ 2 (see margin) by providing answers to sub-questions RQ 1A, RQ 1B, and RQ 2A (see below). The chapter is split into six sections.

The research questions were introduced in Section 1.1 (p. 2) as

RQ 1: *What are engineering students' conceptual difficulties with current and voltage?*

RQ 2: *To what extent can the conceptual difficulties identified before be overcome through the use of existing Tutorial worksheets?*

Section 7.1 presents a detailed analysis of the five bulbs test, a test that probes the most fundamental aspects of KCL and KVL, namely student understanding of current in series connections and of voltage in parallel connections. The test has been used to identify several conceptual difficulties among students in physics courses (McDermott and Shaffer, 1992; McDermott, 2001). In this thesis, the test was given to students in engineering courses. The test results can be used to answer research question RQ 1A:

RQ 1A Are the conceptual difficulties with current and voltage identified in physics courses also prevalent in engineering courses?

Within this research project the five bulbs test was given to students who had participated in a varying number of Tutorial worksheets. Consequently, the test results can also help answer research question RQ 2A:

RQ 2A To what extent is the frequency of the conceptual difficulties reduced when existing Tutorial worksheets are used?

Sections 7.2 to 7.6 address various other aspects of the understanding of current and voltage. In so far as they have been addressed in the context of physics education research (PER), the findings in these sections contribute to RQ 1A. Aspects that have not been addressed in PER contribute to answer RQ 1B:

RQ 1B Are there conceptual difficulties with current and voltage in the electrical engineering curriculum that have not been identified before?

Section 7.2 presents a detailed investigation into students' understanding of KVL using three different tests. These tests all contain a circuit element in parallel to an ideal voltage source and test under which conditions students believe the voltage across that element to change. Since a change of that voltage would constitute a violation of KVL, these tests can reveal how consistently and under which conditions students apply KVL.

Section 7.3 takes a look at student understanding of sources using extreme circuit configurations such as voltage sources connected in parallel. Interviews reveal different misconceptions regarding the electric properties of sources and written tests are used to indicate their prevalence.

Section 7.4 presents a comprehensive study of students' understanding of the voltage across open switches and open circuits. Four different questions developed by different researchers and more than 5500 student answers are compared and evaluated. It is found that about half of the students believe the voltage across an open circuit to be zero. Different types of reasoning that lead to this belief are presented and illustrated using student quotes. The prevalence of these types of reasoning is discussed.

Section 7.5 analyzes students' violations of KCL and KVL in conjunction with open circuits. The frequencies of students' answers that violate the two laws are compared.

Section 7.6 discusses student understanding of short circuits. Previous investigations of short circuits are presented and compared. Two tests conducted at TUHH and Loughborough University are presented and their results analyzed, focusing on the conditions under which students are able to identify a short circuit as such.

Section 7.7 summarizes key findings of this chapter and relates them to research questions RQ 1A, RQ 1B, and RQ 2A.

7.1 THE FIVE-BULBS TEST

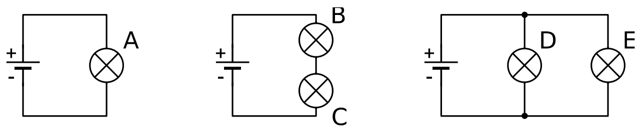
The five-bulbs test by McDermott and Shaffer (1992) is one of the most fundamental tests on DC circuit analysis. As shown in Figure 7.1, it asks students to rank the five bulbs A to E by their brightness. Students' rankings reveal their understanding of the behavior of voltage in parallel connections, current in series connections, and batteries acting as ideal voltage sources. Thus, the test examines the most simple applications of KVL and KCL.

In this section, test results from European (German and British) students in engineering course are compared with results from physics courses in the USA. While the students from the USA were taught traditionally, instruction in Germany and Britain used a varying number of Tutorials.

The correct ranking of the bulbs in the five-bulbs test is A=D=E>B=C. It can be determined as follows: The three batteries are all ideal and identical. Thus, the voltage across them is the same and independent of the current they supply. Bulbs A, D, and E are all

Task 1

The following three circuits contain identical bulbs and identical ideal batteries. (Assume that the batteries are ideal voltage sources, i.e. they have no internal resistance.)



Rank the 5 bulbs by their brightness.
(Please use the relational operators '>', '<', and '='.)

Briefly explain your reasoning.

Figure 7.1: The five-bulbs test, as used at TUHH and Loughborough University.

connected in parallel to a battery. Consequently, the voltage across all of these bulbs is equal to the battery voltage. Since bulbs A, D, and E are identical, they will glow equally bright. Bulbs B and C are connected in series. Thus, the current through bulb B also flows through C. Since these bulbs are also identical, they glow equally bright. The series connection of B and C is in a loop with a battery. Thus, the voltage across each of the two bulbs is less than the battery voltage. As bulbs B and C are identical to bulbs A, D, and E, bulbs B and C will be less bright than bulbs A, D, and E.

The explanation above used the fact that a bulb's brightness is an indicator for the current through and the voltage across it. The larger the current through a bulb, the brighter it glows. The larger the voltage across a bulb, the brighter it glows. Students who work with the Tutorials *Current and Resistance* as well as *Voltage* observe these relationships in experiments. In addition, these relationships are explicitly stated in the Tutorial worksheets. However, students who have not worked with Tutorial worksheets can still answer the questions correctly. Assuming a strictly monotonic (but not necessarily linear) current–voltage characteristic, a larger current through a circuit element will always result in a larger voltage across it, and vice versa. An increase in voltage and current will result in an increased power, which in the case of a bulb causes it to glow brighter. Thus, as long

These Tutorials are described in Appendices B.2 (p. 319) and B.7 (p. 351).

Possible implications of the usage of bulbs in the five-bulbs test are also discussed in Section 7.1.5 (p. 118).

as students relate the brightness of the bulbs to the current through them, the voltage across them, or the power they consume, they will be able to arrive at the correct answer.

It is quite unlikely that students will assume bulbs to have a non-monotonic current–voltage characteristic. While devices with such a characteristic exist (see e. g. Bao and Wang, 2006), they are rarely used. Instead, students' explanations show that they often assume bulbs to behave like ohmic resistors, i. e. having a linear current–voltage characteristic. This assumption is stronger than needed, but has no negative effect on the answers to the test.

7.1.1 *Administration of the Test and Variants Used in Different Cohorts*

The five-bulbs test has been used extensively to assess students' conceptual understanding of basic circuit analysis. McDermott (2001) gathered data on more than 1000 traditionally taught undergraduate students, as well as high school physics teachers, STEM faculty, and graduate teaching assistants (TAs). As can be seen in Table 7.1, the graduate TAs performed best, with an average of 70% correct rankings. In the other three groups, only 15% of the rankings were correct.[1] McDermott (2001) notes that for the undergraduate students, "results have been essentially the same before and after standard instruction".

To allow these data to be compared to engineering students, the test was administered four times at Hamburg University of Technology[2] (TUHH) in Germany and twice at Loughborough University in the UK. The results of these tests are also shown in Table 7.1. The different cohorts as well as the variations of the test that were used are described in the remainder of this subsection. Subsequently, the test results are compared and discussed.

The different courses are described in detail in Section 4.2.

The full tests are shown in Appendices E.1 (p. 388), E.2 (p. 390), E.7 (p. 404), and E.19 (p. 456).

An overview of when individual tests were given in different courses is presented in Appendix A (p. 305).

EE2EE is a second semester electrical engineering course for electrical engineers and students of similar courses of study and is taught traditionally. In this course, the five bulbs test was given twice, once by Kautz (2001) in 2000 and once by the author of this thesis in 2013.[3]

In the course EE1ME, a course that is mostly taught traditionally but also employs a few Tutorials, the five bulbs test was administered twice: Once by Kautz in 2008 and once by the author of this thesis in 2016. In 2008, the test was given in the first week of the course before any Tutorials. In 2016, it was given in the 4th week of the course, when all students had worked through the Tutorial *Cur-*

1 McDermott rounds to the nearest five percent.

2 "Technische Universität Hamburg" in German, formerly "Technische Universität Hamburg-Harburg".

3 The test was administered a third time in 2013 at the end of the semester. Due to low participation and a likely very high self selection bias that administration is omitted here.

Table 7.1: Percentages of correct rankings in the five-bulbs test (see Figure 7.1) for different cohorts.

Cohort	N	Correct Ranking
McDermott (2001)		
Undergraduates	> 1000	15 %
Precollege teachers	> 200	15 %
STEM faculty	> 100	15 %
Graduate TAs	≈ 55	70 %
EE2EE		
2000, Week 8 without Tutorials	146	57 %
2013, Week 1 without Tutorials	238[a]	29 %
EE1ME		
2008, Week 1 without Tutorials	354	25 %
2016, Week 4 with 1 Tutorial	193	39 %
2016, Week 4 with 2 Tutorials	74	59 %
EE1UK		
2017, Week 1 without Tutorial	124	48 %
2017, Week 8 with 6 Tutorials	79	59 %[b]

a Due to an oversight, this test did not ask students to indicate if two bulbs are the same brightness. 25 tests that contained ambiguous rankings were ignored.
b A=D>B=C in addition to "brightness of bulb A stays the same when the switch is closed" in that version of the test.

rent and Resistance, and some students had even worked through the second Tutorial *Voltage*.

Students in the courses at TUHH were not used to see batteries in circuit diagrams. To determine if the use of batteries as sources affected student answers, the test in 2016 consisted of two versions. About half of the students were given the standard version shown in Figure 7.1. The other half were given an alternate version which depicted ideal voltage sources instead of batteries and is shown in Figure 7.2. As the

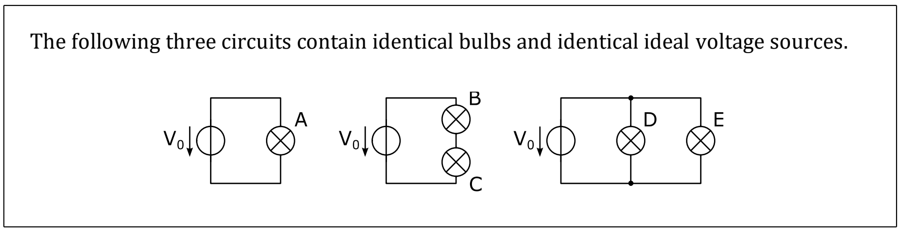


Figure 7.2: Variation of the five-bulbs test with voltage sources instead of batteries. The questions and answer boxes are identical to those shown in Figure 7.1.

symbol used for the source had no effect on the percentage of correct answers, the data for the two versions are combined in Table 7.1.

The course is described in detail in Section 4.2.5 (p. 56).

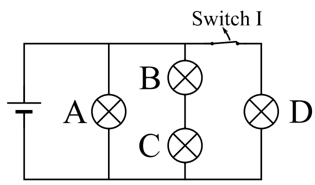
The course EE1UK is an introductory electrical engineering course for automotive engineering students at Loughborough University. In this course, the five-bulbs test was administered in week 1 as a pre-test before any instruction. In week 8, after instruction on DC circuit analysis had been completed, it was also administered as a post-test. The post-test used a modified circuit shown in Figure 7.3. Between the two tests, students worked on Tutorials addressing the topics *Current and Resistance*, *Voltage*, *Multiple Batteries*, *Electric Potential*, *Basic Circuit Analysis*, *RLC-Networks*, and *Phasors*.

7.1.2 *Discussion of Test Results*

Several observations can be made about the test results shown in Table 7.1.

Task 1

The circuit at right contains identical bulbs and an ideal battery. (Assume that the battery is an ideal voltage source, i.e. it has no internal resistance.)
The switch is closed at first.



Rank the 4 bulbs according to their brightness.
(Please use the relational operators '>', '<', and '='.)

Briefly explain your reasoning.

Now, the switch is opened.
By opening the switch, the brightness of bulb A …

- ☐ *increases.*
- ☐ *stays the same.*
- ☐ *decreases.*

Briefly explain your Reasoning.

Figure 7.3: Variation of five-bulbs test used as a post-test in EE1UK.

Firstly, the average performance of all cohorts of engineering students was stronger than that of most of the cohorts reported on by McDermott (2001). Even students tested before any university instruction answered correctly more often (25% and 48% in Week 1 of EE1ME and EE1UK, respectively) than the undergraduate students tested by McDermott (2001).

While the better performance of the engineering students might be attributed to them simply having more interest in or exposure to electrical engineering than the students in McDermott's study, the large difference between 25% correct answers in week 1 of EE1ME and 48% correct answers in week 1 of EE1UK suggests another factor. While exposure to electrical engineering at university was likely similar for students in both courses (EE1ME and EE1UK are the first courses on electrical engineering in the respective study programs) and students in both courses likely have similar interest in electrical engineering (neither course is attended by electrical engineering students), most students in EE1UK had more advanced education on electrical engineering in secondary school than a typical student in EE1ME. In the opinion of the instructor of EE1UK, who is also familiar with education in Germany, his students performed better in many aspects, since they had significant electrical engineering basics as part of their A-levels. If the only difference between the students in EE1ME and EE1UK actually is their secondary education on electrical engineering, the test results would indicate that this more advanced education is still relevant years later.

Secondly, as reported by McDermott (2001), traditional instruction does not significantly affect students' answers to the test. There is virtually no difference between the results of the 2008 test in EE1ME (25% correct rankings) and the 2013 test in EE2EE (29% correct rankings). The test in EE1ME was conducted in the first week of the students' first semester of electrical engineering education. The test in EE2EE was conducted in the first week of the students' second semester of electrical engineering education. Thus, despite the electrical engineering students in EE2EE having finished a whole semester including exams, both groups performed about equally strong.

This equal performance is contrasted by the test results from the course EE2EE in 2000, whose students performed significantly better (57% correct rankings) than those in EE2EE in 2008 (29%). The most likely explanation for this stark gap in student performance is that students in 2000 were tested in the 8th week of the semester, after the introduction of AC circuit analysis. Like the students in 2008, the students in 2000 had been introduced to the concepts relevant for this test at the beginning of their first semester of electrical engineering in the context of DC circuit analysis. But, critically, in the eight weeks of EE2EE they had revisited all of these aspects in the context of AC circuit analysis. This instruction usually emphasizes the similarities between

DC and AC circuit laws, giving students plenty of opportunities to test and revise their understanding of DC circuit analysis. These students likely also attended other courses that discussed or detailed DC circuit analysis.

Thirdly, students who participated in more Tutorials showed much better results than those who participated in less, as can be seen in the course EE1ME. This effect can likely be attributed to the Tutorials, especially since students who participated in 1 and 2 Tutorials had the same amount of traditional teaching and only differed in one recitation section session where the additional Tutorial was worked on. In the course EE1UK the difference in student performance between week 1 (0 Tutorials) and week 8 (6 Tutorials) is less pronounced. Since the concepts tested by the five bulbs test are mainly addressed in the Tutorials *Current and Resistance* as well as *Voltage*, it would not be expected that the additional four Tutorials would affect students' five-bulbs test results much.

In summary, the test results from engineering students with traditional instruction are better than those reported for students in US physics courses. Still, with only half and in most cases even only a quarter of the students correctly ranking the bulbs, student performance after traditional instruction is not as good as is desirable. Tutorials improve student answers, especially in the German courses, where the pre-instruction level was not as good as in EE1UK.

7.1.3 *Student Misconceptions*

McDermott and Shaffer (1992) identified several student beliefs and misconceptions that can be seen as the cause of the incorrect rankings reported upon above. Many of the beliefs and misconceptions observed among students investigated by McDermott and Shaffer can also be found in the explanations given by the engineering students in the courses EE2EE, EE1ME, and EE1UK. The examples shown in this subsection are from the first week of the course EE2EE in 2013, a second semester course for electrical engineering, general engineering, and computer science students. Students in this course had already completed EE1EE, a traditionally taught course on DC circuit analysis and electrostatics. Thus, based on their study program, these students should consider electrical engineering relevant. As they attend their second course on electrical engineering, they should be familiar with the basics.

The different courses are described in Section 4.2 (p. 53).

Misconception: *The direction of current and order of elements matters*

McDermott and Shaffer (1992) reported on the misconception that *the direction of current and order of elements matters*. Students believe that bulb B in the five-bulbs test (see Figure 7.1) would glow brighter than bulb C because the current first passes through bulb B. If a student thinks of the electron flow instead of the conventional current, bulb C would glow brighter. One student explained: "A shines brightest because it is the only load in the circuit. B comes after that because it is the first load in the series connection. Then [...] C because it is the 2nd load of the series connection."[4]

Not all students' explanations state the effects they believe to cause bulbs to glow in a certain brightness. In these cases, students often simply state facts about the circuit, like the number or arrangement of bulbs, instead of an actual explanation of the effects. The student quoted above also used this approach. However, their choice of words could hint at a specific explanation. The student spoke of the bulbs as "loads" in the circuit. The German word for 'load' that they used is 'Verbraucher', which means 'consumer' when translated literally. Thus, this student might believe what several other students (see below) speak of explicitly.

Misconception: *Current is "used up"*

McDermott and Shaffer (1992) report that many students have the misconception that *current is "used up"*. This misconception can also be observed among engineering students. The engineering students, however, avoid the phrase "used up", likely because they have been told that current is actually not "used up". A number of alternative phrases, a combination of technical terms and colloquial language, can be observed: "The electrons arrive first at C, the waste goes to B which thereby glows dimmer."[5] or when using the direction of conventional current "Because most of the current of C was eaten[sic] by B, it glows weakest."[6] and "In the series circuit, on the other hand, the last [bulb] has less juice."[7]

Misconception: *Failure to distinguish between voltage and potential*

This misconception is also discussed in Section 9.4.3 (p. 220).

McDermott and Shaffer (1992) also reported that students believed the potential of a bulb (seemingly always the potential at the upper terminal) determined its brightness. McDermott and Shaffer called this the *failure to distinguish between voltage and potential*. In their tests, this belief occurred about as often as the misconception of current being "used up". The students in the physics courses investigated by McDermott and Shaffer (1992, p. 998) explicitly spoke of "potential" in their explanations. In contrast, the engineering students investigated here did not use the term 'potential'. One student for example ranked the bulbs in the five-bulbs test as A=B=D=E>C and argued "At A, B, D, and E the full voltage is applied. At C not."[8] This argument only makes sense when what these students call 'voltage' is understood as *electric potential*. The engineering students not using the word 'potential' could simply be the result of students being less

4 German original: "A leuchtet am hellsten, da sie der einzige Verbraucher im Stromkreis ist. B kommt danach, weil sie in der Reihenschaltung der erste Verbraucher ist. Danach [...] dann C, weil sie der 2. Verbraucher der Reihenschaltung ist."

5 German original: "An C kommen die Elektronen als erstes an, der Abfall geht an B, dadurch leuchtet die schwächer."

6 German original: "Weil der meiste Strom von C von B verspeißt[sic] wurde, leuchtet sie am schwächsten."

7 German original: "Bei der Reihenschaltung dagegen hat die letzte [Birne] weniger Saft."

8 German original: "An A, B, D, E liegt die volle Spannung an. An C nicht."

exposed to the word. The materials used in the course EE1EE only use the electric potential in the context of electrostatic fields and node voltage analysis.

Misconception: *Failure to recognize that an ideal battery maintains a constant voltage between its terminals*

Misconception: *Batteries behave like ideal current sources*

A different issue reported by McDermott and Shaffer (1992) is the *failure to recognize that an ideal battery maintains a constant voltage between its terminals*. This belief also occurs with the engineering students, even though the five-bulbs test (see Figure 7.1) explicitly states that the batteries can be treated as ideal voltage sources. As in the tests by McDermott and Shaffer, several students assumed in their answer that *batteries behave like ideal current sources*, arguing for example: "The brightness of the bulb depends on the current I. In a series connection (Circuit 1, Circuit 2), the same current flows everywhere. Thus, A, B, and C are equally bright. In a parallel circuit, the current is divided between both branches, and since the lamps are the same, both become equally bright, but less than A, B, and C."[9] While this student does not explicitly refer to a current source, they clearly state that the current from the first two batteries is the same, therefore suggesting that the current from the third battery is also the same. That would only be the case if the batteries behaved as ideal current sources.

Combinations of Misconceptions

Combinations of multiple difficulties or misconceptions are also not uncommon. In combination with the belief that current is "used up", statements such as the following are made: "The total current flows through A. The total current also flows through B, however only the current that is left after the resistor B flows through C."[10] One student, who ranked the bulbs as A=B=C>D=E, even mixed up current and voltage, possibly because they used current-based reasoning but were confused by the problem set-up stating the batteries to behave as voltage sources: "The same amount of voltage flows through A, B, and C. At D and E there is a voltage divider."[11]

Misconception: *Current and voltage can be considered independently*

A different misconception, not explicitly mentioned by McDermott and Shaffer (1992), is that *current and voltage can be considered independently*: "All batteries deliver the same current and voltage. For bulbs B and C, the voltage is divided, but drops off more strongly across B. With D and E the current is divided equally."[12] This student treats current and voltage independently of each other, with current splitting in parallel connections and voltage being divided in series con-

9 German original: "Die Helligkeit der Glühlampe hängt vom Strom I ab. In einer Reihenschaltung (Bild 1, Bild 2) fließt überall der selbe Strom. Also sind A, B, C gleich hell. In einer Parallelschaltung teilt sich der Strom auf beide Zweige auf, und da die Lampen gleich sind, werden beide gleich hell, aber weniger als A, B, oder C."

10 German original: "Durch A fließt der gesamte Strom. Durch B fließt auch der gesamte Strom, durch C aber nur der Strom der nach dem Widerstand B übrig ist."

11 German original: "A, B und C werden von der gleichen Spannung durchflossen. Bei D und E liegt ein Spannungsteiler vor."

12 German original: "Alle Batterien liefern gleiche Stromstärken und Spannung. Bei den Lampen B und C wird die Spannung aufgeteilt, fällt aber über B stärker ab. Bei D und E wird der Strom identisch aufgeteilt."

nections. As this student also assumes a larger voltage drop across B than across C, they rank bulb B brighter than bulbs D and E. This unequal drop of voltage across bulbs B and C could be caused by the belief of current being "used up" or a confusion between voltage and potential. Another student also treated current and voltage independently, but believed the voltage across B and C to be equal. They ranked the bulbs as $A>B=C=D=E$ and reasoned: "Power is equal to $P = V \cdot I$. With bulb A, the entire current and the entire voltage goes through the bulb. With the B/C circuit, the voltage is divided equally between the two bulbs (since the bulbs are identical). With the D/E circuit, the current is divided."[13] In their answer, the student obviously ignored the current–voltage characteristic of the bulbs. Their answer fits neither a strictly monotone characteristic, nor the linear characteristic of Ohm's Law. Based on informal observations by the author, it seems likely that students who consider current and voltage independently simply do not think about applying Ohm's Law or any other current–voltage characteristic, even though they are in principle able to.

The independent consideration of current and voltage also appears in an abbreviated form, where students state that "current is divided" in the parallel circuit and "voltage is divided" in the series circuit. In the even more extreme form, students simply state that in the first circuit, there is only one bulb, in the second, there is a series connection, and in the third, there is a parallel connection.

This reasoning might be founded in a *tendency to reason sequentially and locally, rather than holistically*, that McDermott and Shaffer (1992) described. The students quoted above correctly observed that the two bulbs in the second circuit are connected in series and correctly deduced that the voltage across them is split in half. They also correctly observed that the two bulbs in the third circuit are connected in parallel and correctly deduced that the current going into this parallel connection is split evenly between the bulbs. What these students failed to account for is how the total resistance of these configurations influences the current supplied by the battery.

Misconception: *Tendency to reason sequentially and locally, rather than holistically (1 of 2)*

The different quotes presented above indicate that the engineering students investigated in this study in principle hold the same incorrect beliefs and misconceptions as students of other study programs reported upon in literature. It is, however, difficult to determine the frequency of these beliefs and misconceptions as many students did not write any explanation in the ungraded quizzes used in this study and several of the explanations given are vague.

13 German original: "Leistung ist gleich $P = U \cdot I$, bei Lampe A geht der gesamte Strom & die gesamte Spannung über die Lampe. Bei der Schaltung B/C teilt sich die Spannung auf beide Lampen gleichmäßig (da Lampen identisch) auf, bei Schaltung D/E entsprechend der Strom."

7.1.4 *Analysis of Specific Relations*

The previous section showed several student beliefs and misconceptions that lead to incorrect rankings in the five-bulbs test. As described above, the frequency of these beliefs and misconceptions cannot be determined based on students' explanations of their answers. The students' rankings however, can be broken down into specific relations between the individual bulbs. The analysis presented below will describe students' beliefs that likely correspond with specific relations. Based on the frequency of the individual relations, it is possible to estimate the frequency of certain beliefs. However, it has to be stressed that the correspondence between students' beliefs and given relations is only a best guess.

Five relevant relations are shown in Table 7.2. For each relation, the percentages of students who used it in their ranking is given in the table. The relations investigated here are all incorrect as this analysis focuses on misconceptions.

Students who rank A=B>C or A=C>B either believe the brightness of a bulb to be determined by its electric potential (failure to distinguish between voltage and potential) or they believe the batteries to behave as ideal current sources and current to be "used up". The order of B and C depends on the direction of current that these students

Table 7.2: Answers to five-bulbs test split into different relations for some of the data shown in Table 7.1.

		Frequency of incorrect relations				
Cohort	N	A=B>C OR A=C>B	A>B>C OR A>C>B	A=B=C	D≠E	A≠D OR A≠E
EE2EE						
2000, Week 8 without Tutorials	146	0 %	8 %	1 %	1 %	34 %
2013, Week 1 without Tutorials	238[a]	5 %	24 %	7 %	5 %	67 %
EE1ME						
2008, Week 1 without Tutorials	354	9 %	18 %	11 %	14 %	64 %
2016, Week 4 with 1 Tutorial	193	3 %	15 %	8 %	18 %	49 %
2016, Week 4 with 2 Tutorials	74	0 %	5 %	0 %	11 %	32 %
EE1UK						
2017, Week 1 without Tutorials	124	0 %	19 %	3 %	2 %	41 %
2017, Week 8 with 6 Tutorials	79	0 %	4 %	3 %	1 %[b]	35 %[c]

a Due to an oversight, this test did not ask students to indicate if two bulbs are the same brightness. 25 tests that contained ambiguous rankings were ignored.
b A≠D in that version of the test.
c The "brightness of bulb A increases or decreases when the switch is closed" in that version of the test.

assume. Of the three relations about bulbs A, B, and C discussed here, this is the least common one. Students who rank A>B>C or A>C>B likely believe current to be "used up", but do understand that the current through the battery is smaller for the circuit with the larger load. Again, the order of B and C depends on the direction of current students assume. Students who rank A=B=C likely believe the batteries to behave as ideal current sources. Students who relate D≠E likely believe that the order of bulbs in a parallel connection matters, possibly due to localized reasoning. Students who relate A≠D or A≠E (in most cases A>D=E) fail to recognize that an ideal battery maintains a constant voltage between its terminal.

The incorrect relation A≠D or A≠E was given most often in every cohort. The statement D≠E, in contrast, was made much less often. Thus, while only some students believe that the order of bulbs in a parallel connection is of importance, a large fraction of students fails to recognize that the voltage across the batteries is constant. The following Sections 7.2 and 7.3 further investigate students' understanding of sources and of elements connected in parallel to them.

In the tests conducted in the courses EE1ME and EE1UK the frequency of the incorrect statements overall decreased the more Tutorials a cohort had participated in. This decrease in incorrect relations is particularly clear in the course EE1ME. In week 4 of the 2016 course, some of the students had participated in 1 Tutorial, while others had participated in 2 Tutorials. The students who had participated in 2 Tutorials stated the incorrect relations less often. Except for this one Tutorial, all students had the same instruction. Thus, the better performance of the second group can be attributed to the Tutorial. Similarly, the students who had participated in 1 Tutorial in 2016 less frequently stated incorrect relations than the students in week 1 of 2008, who had not participated in any Tutorial.

This positive impact of the Tutorials could also be attributed to an effect called *teaching to the test*. Students could actually not have understood the concepts tested in the five-bulbs test and simply performed better because they were familiar with the specific circuit used in the test due to their instruction. The three circuits used in the five-bulbs test also appear in the Tutorials. However, exam resuts in the course EE1ME in 2012, 2013, 2014, and 2015 (see Appendices E.6, E.11, E.14, and E.18) indicate that the improvement in students' performance was not a result of teaching to the test. The exams used in the course contained questions that used different circuits than the Tutorial, but also tested the statements A>B, A>C, and B=C, as well as in one case D=E. Students who participated in the exams also had instruction using Tutorials. In all but one instance, the students in the exams performed better than the students in Table 7.2 who had participated in two Tutorials. Thus, it seems likely that students who participated in the Tutorials were able to apply the concepts they had learned in the Tutorials to other circuits. Further evidence for this interpretation is presented on page 199 in Section 8.2.7, where student statements about bulbs B and C are compared with another circuit configurations.

7.1.5 *Usage of Batteries and Bulbs*

A common criticism of tests such as the five-bulbs test is the use of batteries and bulbs. Both components are rarely used in traditional electrical engineering courses, which often focus on quantitative tasks and instead use voltage sources and resistors (see e. g. Ameling, 1988; Hagmann, 2011; Hambley, 2008; Warnes, 1994). Engineering students who have not had contact with Tutorials will in many cases have no experience with circuits that contain batteries and bulbs. This might make it more difficult for them to answer qualitative questions such as the five-bulbs test. Several students who had not worked with Tutorials explicitly remarked in their answers to the five-bulbs test that batteries were not part of their curriculum.

The use of batteries and bulbs might require more effort on the part of students who are not familiar with such symbols. Based on the way bulbs and batteries are used in such qualitative tests, however, it is unlikely that these students experience any disadvantage that could not be compensated by allowing them more time.

The use of bulbs can hardly result in incorrect answers. As discussed in the introduction of this section on page 107, the brightness of a bulb is an indicator for the current through it, the voltage across it, and the power it consumes. Assuming bulbs to behave as Ohmic resistors also results in correct answers. Thus, every reasonable assumption on how the brightness of a bulb is related to current and voltage in the circuit will result in a correct answer.

While many students do not know how to model the behavior of real life batteries, the five-bulbs test explicitly tells students to treat batteries as ideal voltage sources. A test was used to determine the effect caused by the usage of batteries instead of voltage sources. Two different versions of the five-bulbs test were used in the course EE1ME. One version used batteries which were said to behave as ideal voltage sources (see Figure 7.1), the other version used ideal voltage sources (see Figure 7.2). When handing out the tests, the two versions were on alternating sheets of paper, resulting in a random split of the students in the course.

Table 7.3a shows the number of correct and incorrect rankings for both versions of the test, the one with batteries and the one with ideal voltage sources. The χ^2 test can be used to show that the answers for both versions are so similar that it is not likely that the differences that are observed here are a result of the two tests having a different difficulty ($p(\chi^2) = 0.327 > 0.05$). In contrast, Table 7.3b

The χ^2 test is described in Section 5.3.5 (p. 69).

Table 7.3: Dependence of five-bulbs test results on symbol used for the source and number of Tutorials completed for students in the course EE1ME in 2016.

(a) $p(\chi^2) = 0.327$

	Source Symbols	
Ranking	Batteries	V. sources
correct	57	63
incorrect	79	68

(b) $p(\chi^2) = 0.004$

	No. of Tutorials	
Ranking	1	2
correct	76	44
incorrect	117	30

Table 7.4: Student answers from Table 7.3 split into different statements.

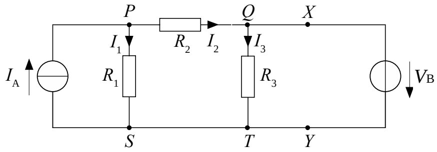
			Frequency of incorrect relations				
Cohort	N	Correct Ranking	A=B>C OR A=C>B	A>B>C OR A>C>B	A=B=C	D≠E	A≠D OR A≠E
V. Sources	131	48 %	4 %	11 %	2 %	17 %	42 %
Batteries	136	42 %	0 %	13 %	10 %	15 %	47 %
1 Tutorial	193	39 %	3 %	15 %	8 %	18 %	49 %
2 Tutorials	74	59 %	0 %	5 %	0 %	11 %	32 %

shows the same data, but split by the number of tutorials that a Student had participated in. The difference in the answers is significant ($p(\chi^2) = 0.004 < 0.05$). The better performance of the students who had participated in two Tutorials instead of just one is likely caused by these students having developed a better understanding of electric circuits.

Thus, students whose test contained voltage sources instead of batteries did not perform better, but students who had participated in two Tutorials performed better than those who only participated in one. While all students had participated in at least one Tutorial, it seems unlikely that this one Tutorial resolved all difficulties with batteries but not all difficulties that occur in the five-bulbs test. It is more likely that the use of batteries instead of ideal voltage sources does not increase the difficulty of the test.

Table 7.4 shows the percentages of correct rankings for all four groups as well as the frequency of specific relations in their rankings. The frequency of incorrect relations is about the same for students whose test included batteries compared to those whose test included voltage sources. However, the group that completed 2 Tutorials stated incorrect relations less frequently than the group that completed 1 Tutorial. The difference between these two groups is especially strong with the statement A≠D and A≠E, which is strongly

1. The circuit at right contains a current source I_A, a voltage source V_B, and the resistances R_1 to R_3. I_1 and V_1 denote the current and the voltage at R_1, etc. The values of I_A and V_B are positive.



The value of the source current I_A is now increased. For each of the following quantities, state if its value changes or stays the same.

Please give a short *explanation* of your answer.

a. V_3 ☐ changes ☐ stays the same
Reasoning:

b. I_3 ☐ changes ☐ stays the same
Reasoning:

Figure 7.4: Test with a resistor connected in parallel to a voltage source and a varied current source. This test was used in a quiz in EE1ME in 2012 (Appendix E.5).

related to the content of the second Tutorial titled *Voltage*. These results also indicate the different symbols used for sources do not effect the test results, but that the Tutorial effected students' beliefs about electric circuits, in particular about aspects of electric circuits that it addressed.

7.2 ELEMENTS CONNECTED IN PARALLEL TO VOLTAGE SOURCES

A discussion of this difficulty can be found on p. 114.

Misconception: *Failure to recognize that a voltage source maintains a constant voltage between its terminals*

The aspect of the five-bulbs test that was most difficult for the engineering students was the correct application of KVL for bulbs connected in parallel to a battery. While most students correctly identified the two parallel bulbs D and E to be equally bright, many believed the single bulb A to be brighter than D and E. McDermott and Shaffer (1992) named this difficulty a *failure to recognize that an ideal battery maintains a constant voltage between its terminals*. This difficulty, however, not only occurred when students were given circuits that depicted ideal batteries as the source and stated that these should be treated as voltage sources, but also when students were given circuits that depicted voltage sources as the source. This difficulty is therefore better described as a *failure to recognize that a voltage source maintains a constant voltage between its terminals*, as contradictory as that may sound. The following three subsections investigate this failure using three different circuit configurations.

7.2.1 *Varied Source*

The full test is presented in Appendix E.5 (p. 398).

The test shown in Figure 7.4 was conducted in the course EE1ME in 2012 in the 11th week of the course after students had participated

Table 7.5: Students' answers to the question shown in Figure 7.4. $N = 324$.

	I_3 changes			
V_3 changes	no	yes	*n/a*	Sum
no	33 %	13 %	1 %	46 %
yes	2 %	47 %	1 %	49 %
n/a	0 %	2 %	2 %	5 %
Sum	35 %	61 %	4 %	100 %

in three Tutorials. This test used a voltage source and, unlike the five-bulbs test, resistors instead of bulbs. The part of the question shown here asked students if the voltage V_3 and the current I_3, i. e. the voltage across and the current through resistor R_3, would change when the current I_A was increased. As R_3 is connected in parallel to the voltage source V_B, V_3 must remain constant and based on Ohm's Law, I_3 must then also remain constant.

Table 7.5 shows the distribution of students' answers to the two questions. There are three dominant answer combinations. One third of the students (33%) correctly stated that neither the voltage across nor the current through R_3 would change. Another 13% stated that the current would change, but the voltage would not. The largest group (47%) stated that both the voltage and current would change. Virtually all students who believed the voltage to change also believed the current to change. An investigation of their explanations showed that they mostly reasoned based on Ohm's Law. I_3 changed, so $V_3 = R_3 \cdot I_3$ must also change. Thus, the distribution of answers in Table 7.5 is better described as ⅓ of students believing neither I_3 nor V_3 to change, while about ⅔ believe I_3 to change. Of these, ¾ believe V_3 to also change because of Ohm's Law.

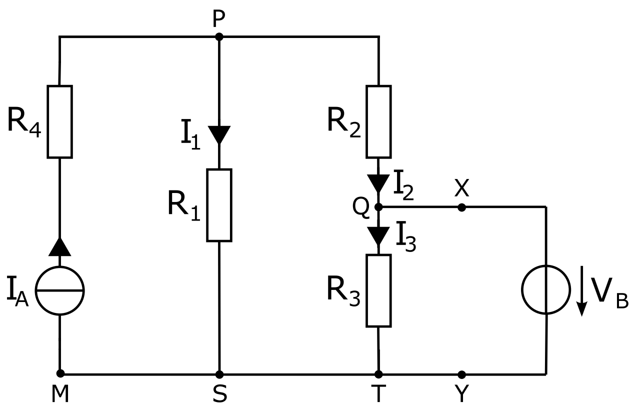


Figure 7.5: Circuit used in student interviews (Appendix F).

In the interviews described in Appendix F, a similar question was used. Students were given the circuit shown in Figure 7.5 and asked if the current through R_3 changed when the source current I_A was changed but the source voltage V_B remained the same. Later, students were asked if the voltage across R_3 changed in that situation. The answers students gave in the interviews match the answering pattern to the test shown in Figure 7.4.

When asked if the current through R_3 changed, students in the inverviews mostly argued based on the path of the current from I_A. I_A splits into I_1 and I_2. Then, I_2 splits into I_3 and the current through V_B. Thus, they argued incorrectly, I_3 is affected by I_A, and when I_A increases, I_3 must also increase. Some students even correctly noted that this argument can only be valid if the resistances of the circuit elements remain the same, with one of them stating that "the resistances remain the same, thus the ratios remain the same, by which [the current] is divided here. It's a current divider. Thus, I would say, yes [I_3] increases."[14] While a few students even mentioned the superposition principle in their answer, none of the students who based their answer on the path of the current from I_A recognized that when using the superposition principle the resistance of the voltage source is zero and thus all of the current from the current source flows through the voltage source and none of it through R_3. Thus, when using KCL at point Q, they did not take into account the $0\,\Omega$ equivalent resistance of the voltage source.

Some of the students who based their answer about I_3 on the path of the current from I_A then used Ohm's law to determine V_3. Since they had determined I_3 to change, $V_3 = R_3 \cdot I_3$ would also change. These students ignored the voltage source V_B in their answer. Two other students based their answer about I_3 on the path of the current from I_A, but used KVL to determine that V_3 is equal to V_B, i.e. remains constant. One of these students immediately recognized that their answer of the current changing but the voltage staying the same violated Ohm's Law. The student, however, was unable to identify the mistake they had made.

Students who answered correctly in general seemed to have no trouble answering the question and appeared more convinced of their answers than those who did not answer correctly. The students who answered incorrectly were quite diverse in their answering behavior. While some gave quick but incorrect answers of which they seemed to be sure, others took a longer time to answer and seemed less sure of not only their answer but also of their approach to find it.

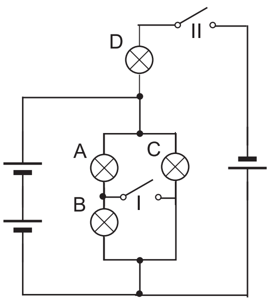
To further investigate the frequency of these difficulties, two additional written tests were used.

14 German original: "die Widerstände bleiben gleich, d. h. auch die Verhältnisse bleiben gleich, wie sich [der Strom] hier aufteilt. Ist ja ein Stromteiler. Dann würde ich sagen, ja [I_3] erhöht sich."

Task 1 (6 points)

The circuit at right contains identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery. The four bulbs are identical. All occurring voltages are within operating range of the bulbs.

Give a short reasoning for every answer to the following questions.



		Answer
a)	(2 points) The switches I and II are open:	
c)	(2 points) Switch I is now open again. Switch II is closed: Does bulb C glow *brighter*, *equally bright* or less bright than in Question a)? Which of the four bulbs glows brightest?	
Reasoning:		

Figure 7.6: Question with an embedded circuit connected in parallel to two batteries and a second branch. This question was part of three tests (Appendices E.3, E.4 and E.7).

7.2.2 *Embedded Circuit*

The question shown in Figure 7.6 uses a circuit that consists of an outer and an inner part. The inner part is composed of three bulbs and a switch arranged in a bridge structure. The outer part can be split in two. On the left-hand side of the circuit, two batteries are connected to the inner circuit, holding it at a constant voltage. On the right-hand side, one bulb, switch II (initially open), and a battery are connected. While switch II is open, no current flows through this part of the circuit. When switch II is closed, it forms a circuit with the two batteries at left, effectively resulting in bulb D being in series with three batteries. The inner circuit (bulbs A, B, and C) is not affected by the closing of switch II, as the voltage across that part of the circuit is still held constant by the two batteries at left. Question c) shown in Figure 7.6 asks students how bulb C changes in brightness when switch II is closed.

The question was used three times, once as an exam in the course EE1ME and twice in EE2EE as an ungraded quiz.[15] While the version used in EE1ME and the one used in EE2EE in 2012 used batteries, the test used in 2013 in EE2EE used voltage sources. The exam in

The full tests are shown in Appendices E.3 (p. 392), E.4 (p. 394), and E.7 (p. 392).

The course EE2EE is described in Section 4.2.3 (p. 56).

15 A fourth use is not discussed here, as only a small number of students participated in that test, likely resulting in a strong self-selection bias.

Table 7.6: Comparison of answers to the question shown in Figure 7.6.

			After closing switch II, bulb C is ... bright			
Cohort	Source	N	less	equally	more	*no answer*
EE1ME						
2011, Week 14	Batteries	561	54 %	27 %	14 %	4 %
EE2EE						
2012, Week 15	Batteries	103	50 %	25 %	21 %	4 %
2013, Week 1	V. Sources	265	39 %	26 %	23 %	12 %

EE1ME in 2011 was administered one week after the end of lectures, while the 2013 test in EE2EE was administered in the first week of the semester. As EE2EE is a second-semester course that follows EE1EE, the students in EE1ME in 2011 and in EE2EE in 2013 had about the same amount of instruction. The students in EE1ME, however, had participated in two Tutorials, while those in EE2EE had only received traditional instruction. The 2012 test in EE2EE was administered one week after the end of lectures, a few weeks before the exam. Thus, students in that course have had almost a full semester more instruction. In general, the course EE2EE can be considered at least as demanding as EE1ME, and students in EE2EE can likely be considered to be more interested in the field of Electrical Engineering.

As can be seen in Table 7.6, the percentage of correct answers (bulb C equally bright) in all three tests is almost identical. While there are some differences in the frequencies of the other answers, these only affect which incorrect answer or non-answer students selected. The students in the 2012 course, who had completed two semesters of traditional instruction did not perform better than the students in the other two cohorts, who had one semester of instruction. Notably, the students in EE1ME, who had participated in two Tutorials, did not perform better than those students in EE1EE, who had not participated in any Tutorials. The Tutorials seem to have no effect on students' understanding of the concepts tested here.

Table 7.7 shows the explanations of all students in the course EE1ME in 2011 who gave an answer to the question. The explanations are split into ones based on current, on voltage, and on *other* concepts, mostly the arrangement of the circuit elements, e. g. the batteries pointing in opposite directions. Answers that contained no explanation are also included in the table. The incorrect answer that bulb C becomes *less bright* when switch II is closed was particularly often explained based on less current flowing through the bulb. The majority of explanations for the correct answer (the bulb stays equally bright) were mostly based on voltage.

Table 7.7: Students' answers and explanations in EE1ME 2011 for all students that answered the question shown in Figure 7.6. N = 537.

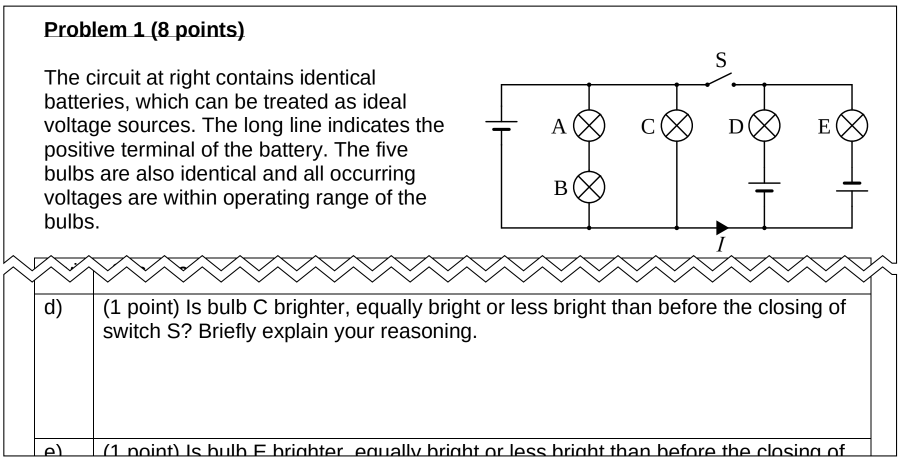
		Explanation primarily based on			
Bulb C is	N	current	voltage	other	*none*
less bright	304	57 %	11 %	20 %	12 %
equally bright	153	19 %	36 %	25 %	20 %
more bright	79	27 %	24 %	24 %	25 %
all answers	536	41 %	20 %	22 %	21 %

In the test reported on in the previous section, 33% of students (see Table 7.5) correctly stated that neither the voltage across nor the current through the element would change. In this test, between 25% and 27% stated that the brightness of the bulb would remain the same. Based on students' explanations, the majority of incorrect answers in both tests was caused by current-based reasoning in situations that required the application of KVL. This test is one of many in this thesis in which students would likely have benefited from using the electric potential when solving the task. A thorough discussion of the benefits of using the electric potential can be found in Chapter 9.

7.2.3 *Sequential Circuit*

The third test used a different circuit in which the source, the bulb under investigation, and the switch were arranged in a sequential manner. This test is shown in Figure 7.7. It was used in an Exam of

The full tests are shown in Appendices E.6 (p. 402) and E.9 (p. 414).


Problem 1 (8 points)

The circuit at right contains identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery. The five bulbs are also identical and all occurring voltages are within operating range of the bulbs.

d)	(1 point) Is bulb C brighter, equally bright or less bright than before the closing of switch S? Briefly explain your reasoning.
e)	(1 point) Is bulb E brighter, equally bright or less bright than before the closing of

Figure 7.7: Question with bulbs connected in parallel to a battery and a sequential circuit that can also be connected in parallel. This question was used in the exam of EE1ME in 2012 and in a quiz in EE3EE in 2013 (Appendices E.6 and E.9). Depicted is circuit version ABC.

Table 7.8: Students' answers to the question shown in Figure 7.7.

			After closing switch S, bulb C is ... bright			
Course	Version	N	less	equally	more	*no answer*
EE1ME	ABC	232	16 %	46 %	37 %	0 %
	CAB	215	11 %	59 %	27 %	4 %
EE3EE	ABC	92	12 %	50 %	32 %	7 %

The course EE3EE is described in Section 4.2.4 (p. 56).

EE1ME, and in a quiz in the EE3EE, a third semester course for electrical engineering students. Question d) of that test, which is shown in Figure 7.7, had the same goal as the question discussed in the previous section. It was designed to test if students were able to recognize that the voltage across bulb C is fixed, as that bulb is connected in parallel to a battery, which can be treated as a voltage source.

In the exam in EE1ME, two versions of the test were used to prevent cheating. Version ABC is shown in Figure 7.7. Version CAB used a modified circuit where the branches with bulbs A, B, and C are switched. This modified circuit is shown in Figure 7.8. When the exam question was designed, the change was considered to not effect student performance. In the exam, this alternate version also had different labels for the bulbs, as can be seen in Appendix E.6. To avoid confusion, the bulb names were modified here to be consistent between versions. The different bulb names in the two versions of the exam meant that students could not simply copy their neighbor's result, since students sitting next to each other were given different versions of the exam.

As can be seen in Table 7.8, the distribution of answers to both questions is, by and large, similar for all three cohorts. The correct answer (bulb C does not change in brightness) is the most common answer in all three cohorts, the second most common answer is that the bulb increases in brightness and the third most common answer is that it becomes less bright. However, there are some differences in the frequency of the correct answer for the three groups. The frequency of correct answers differs more between the two versions of the test in the course EE1ME than between the two tests using version ABC

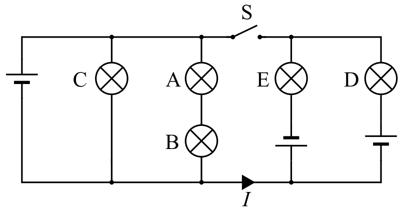


Figure 7.8: Circuit version CAB for the question shown in Figure 7.7. This circuit was used in half of the exams of the 2012 EE1ME course.

Table 7.9: Number of correct and incorrect answers for the data in Table 7.8

(a) Answers in course EE1ME. $N = 447$, $p(\chi^2) = 0.01$

	Version	
Answer	ABC	CAB
correct	107	125
incorrect	125	90

(b) Answers for version ABC. $N = 227$, $p(\chi^2) = 0.54$

	Course	
Answer	EE1ME	EE3EE
correct	107	46
incorrect	125	46

which were administered in EE1ME and EE3EE. While the students in the more advanced course EE3EE performed better in the test than those in the EE1ME who used the same version, the students in the course EE1ME who were given the CAB version performed even better. This effect likely occurs as in the CAB version of the test, the bulb in question is closer to the battery.

Table 7.9 highlights the difference between the two version and courses. Table 7.9a lists the correct and incorrect answers in the course EE1ME for both versions of the test. Table 7.9b lists the correct and incorrect answers for the ABC version in the courses EE1ME and EE3EE. The probability that the difference between the correct and incorrect answers is caused by the version of the test or by the course students were attending can be calculated using the χ^2 test. With a probability of $p(\chi^2) = 0.01 < 0.05$, the χ^2 test indicates that the difference between the correct and incorrect answers for the ABC and CAB versions of the test is significant and thus not based on a simple sampling error. Students more often answer correctly when the bulb in question is closer to the battery. In contrast, the differences in answers to the ABC version in the courses EE1ME and EE3EE, is not significant ($p(\chi^2) = 0.54 > 0.05$). Any differences in the answers between the two courses are likely due to sampling error.

The χ^2 test is described in *Section 5.3.5 (p. 69).*

Thus, while the amount of instruction seems to have no effect on the answers to this question, the proximity of the element to the voltage source does. To correctly answer the question students need to apply KVL. They seem to do this more often when the loop is smaller, or the elements are parallel to each other without any other branch in between.

7.3 IDEAL SOURCES

As mentioned in Section 7.1.5, the use of batteries as sources in qualitative tasks is often criticized as bulbs and batteries are rarely used in traditional instruction. Still, many of the results reported above showed that students over all did not perform differently when ideal voltage sources were used instead of batteries. Thus, some of the student difficulties with the tests presented above could be the result of difficulties with ideal voltage sources as which batteries are modeled in instruction or with ideal current sources as which many students believe batteries to behave.

In the following, student understanding of voltage sources and current sources is investigated with the use of extreme cases, i. e. two voltage sources connected in parallel or two current sources connected in series. Such circuit configurations are not without problems, and the instructor of EE1ME rightly objected to the use of such a configuration in an exam. While his main argument was that such a configuration was not discussed in the course, it is also necessary to point out that such configurations are electrically ambiguous. With two ideal voltage sources connected in parallel, the current through each source is not defined. With two ideal current sources in series, the voltage across each source is not defined. Only the sum current and sum voltage are defined. Some textbooks reason that the current and voltage are divided equally between the two sources due to symmetry. Still, every other ratio would also satisfy KVL and KCL. In "regular" circuits such configurations do not appear. Furthermore, such circuit configurations cannot be analyzed using superposition. When using the superposition principle, the currents and voltages in the circuit are calculated separately for each source, while the voltage sources not considered at the time are replaced with a short circuit and the current sources not considered at the time are replaced with open circuit. With this approach, two voltage sources in parallel would result in one source parallel with a short circuit, i. e. a short-circuited voltage source. Two current sources in series would result in a current source in series with an open circuit, i. e. an open circuit with a current going through it.

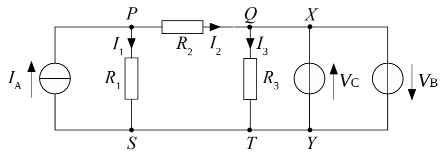
These circuit configurations are used here to prompt students to detail their understanding of ideal sources as well as current and voltage. Students' confusion as a result of any of the issues described above should not be seen as a failure on their part.

7.3.1 *Voltage Sources in Parallel*

The full test is presented in Appendix E.5 (p. 398).

In an ungraded quiz given to students in EE1ME in 2013, students were asked if a voltage source could be inserted in parallel to an existing voltage source *if the currents in the rest of the circuit were to remain the same*. The question is shown in Figure 7.9. As the question was in a free-response format, there is a large array of different answers. Possibly due to the question being unusual, the largest group (24%) were blank answers. The correct answer ($V_C = -V_B$) was given by 18% of students. Another group (6%) answered $V_C = V_B$. These students likely recognized that the two voltage sources must have the same value due to KVL or simply because they are connected in par-

2. In the circuit from task 1, a new voltage source V_C shall be added between the nodes X and Y. The arrow indicating the direction of the voltage shall point upwards, as shown in the picture.



a. Which values may V_C take, so that the currents through the resistors R_1 to R_3 ***stay the same?*** State explicitly, if this is not possible for any value of V_C. Briefly explain your reasoning.

b. Which values may V_C take, if the currents through the resistors R_1 to R_3 ***may change?*** State explicitly, if this is not possible for any value of V_C. Briefly explain your reasoning.

Figure 7.9: Question with two voltage sources connected in parallel. This question was used in a quiz in EE1ME in 2012 (Appendix E.5).

allel, but either made a mistake with the sign or did not correctly understand the (passive) sign convention. Further 17% of students believed that the voltage source could be inserted with $V_C = 0\,V$ while 16% stated that it would be impossible to insert the source at all.

When asked if and with what value V_C could be inserted when the currents were allowed to change, the answers changed dramatically. Now, almost half of the students (44%) did not give an answer. While it is possible that the students simply ran out of time, this is unlikely as such tests are usually only ended once most students have finished answering the test. Thus, it is likely that these students did not know how to answer the question. Only 4% of students correctly answered that the source could be inserted with $V_C = -V_B$. The largest group of answers (20%) was that V_C could be inserted with any value and 8% believed that the voltage source could be inserted with $V_C = 0\,V$. Only 2% of students chose the correct answer ($V_C = -V_B$) for both questions.

The interviews described in Appendix F were used to better understand students' reasonings. They contained a very similar question: After examining the circuit shown in Figure 7.5, students were asked if a voltage source V_C could be inserted between the points X and Y, as shown in Figure 7.10 so that the currents I_1 to I_3 would not change. Students were also asked what the source voltage of V_C could be. Afterwards, students were asked if the source could be added if the currents I_1 to I_3 were allowed to change and what the source voltage V_C could be in that case.

One student completely ignored KVL in their answer. The student instead believed that voltage is the speed of current and that voltage sources accelerate and decelerate the current: "The current always flows in a certain direction and in this case along these arrows (points

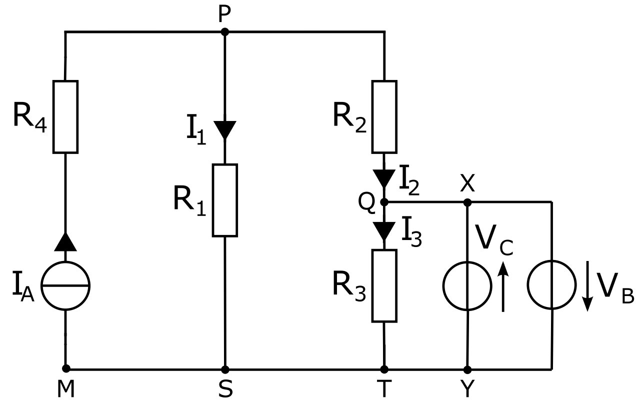


Figure 7.10: Variation of the circuit used in student interviews with a second voltage source (V_C) connected in parallel to the existing one (V_B). Original circuit shown in Figure 7.5.

to the current arrows I_A, I_1, I_2, and I_3), which are given here. V_B also points in the same direction but V_C in the opposite direction of these arrows so it will form a sort of a resistance in the flow direction. This means that the electrons flowing through this wire (pointing to V_B) will be slowed down by the reverse voltage."[16]

Two students used KVL in their interview, but did not apply it to the parallel voltage sources.

The first of these started their argument by comparing voltage sources to batteries and then incorrectly describing the properties of batteries: "With batteries it was the same, when you connect them in series, the current increases, when you connect them in parallel, the voltage increases."[17] Remembering the passive sign convention, the student noted that V_C must have a negative value, as otherwise V_B and V_C would form a loop and "everything" would just circle between the two sources. If V_C were inserted with a negative value, the student concluded, the additional source could be added and the voltages of the two sources would add up. Even when the student a few moments later correctly applied KVL to determine the voltage V_3, they did not realize that their statement about the additional voltage source violated KVL. Instead, the student applied KVL to the loop of R_3 and V_C to show that V_3 now is determined by V_C instead of V_B.

A second student also believed that the additional voltage source in parallel would increase the voltage, but correctly assessed that an increase in the voltage would also increase the currents I_1 to I_3 and

16 German original: "Der Strom fließt ja immer in ne bestimmte Richtung so und in diesem Fall ja entlang dieser Pfeile (zeigt auf die Strompfeile I_A, I_1, I_2 und I_3), die ja hier gegeben sind. So und U_B zeigt ja auch in dieselbe Richtung, aber U_C in entgegengesetzte Richtung dieser Pfeile, also wird sie einen gewissen Widerstand bilden für die Fließrichtung. Das heißt die Elektronen, die durch diese Leitung (zeigt auf U_B) fließen, werden durch die Gegenspannung verlangsamt."

17 German original: "bei Batterien war das auch so, wenn man die in Reihe schaltet dann erhöht sich der Strom und parallel erhöht sich die Spannung"

thus concluded that V_C had to be zero. Immediately afterwards, the student applied KVL to the loop of V_B and V_C and recognized that the absolute values of both sources must be equal. Still, the student maintained that this additional source would affect the currents in the rest of the circuit.

Both of these students showed in their interview that they were able to apply KVL as an equation. But it seems KVL to them is only an equation they can use to determine a voltage based on other known voltages. These students were not able to see the effect and consequences of KVL, how it relates the voltages in a circuit with each other. Their misconception that *source voltages of voltage sources in parallel add up* is stronger than KVL. These students' answers also fit an observation from Engelhardt (1997), who reported that 21% of students believed two batteries in parallel would provide more voltage (p. 157).

Misconception: *Source voltages of voltage sources in parallel add up*

Another student showed a similar inconsistency in their understanding. The student applied KVL, but did not see how it would help them to answer the question: "If you put a loop through here, [...] then you would have $V_C + V_B = 0$. Then V_C would have the value $-V_B$. But that [...] doesn't help me. [...] I can hardly imagine that V_C can only take the value $-V_B$. That doesn't make sense to me somehow."[18]

There also were students who correctly answered the question as well as students who correctly answered that the voltages V_B and V_C must be the same (even though they missed the sign), but still believed this circuit configuration to not be allowed: "There is already one [source], so for me it's just illogical. Why should I add another one? I can't explain that, but for me it's just illogical... because this one already generates voltage why should the other one also generate voltage? [...] V_B is parallel to V_C, so V_B would be equal to V_C and therefore this is actually superfluous I would say, because they have the same voltages."[19] These students' confusion likely originated from the fact that with two voltage sources in parallel, only the sum of the current through them is defined, as noted on p. 128.

The answers of several students showed an incorrect understanding of voltage sources, often accompanied by a failure to understand KVL and its meaning. It seems likely this incorrect understanding of sources is caused by a failure to understand the concept of voltage, evidenced by students' incorrect or missing understanding of KVL.

18 German original: "Wenn man hier eine Masche durchlegt, [...] dann hätte man ja $U_C + U_B = 0$. Dann müsste U_C auf jeden Fall $-U_B$ sein. Aber das [...] bringt mich jetzt [...] nicht weiter. [...] Das kann ich mir irgendwie gerade schlecht vorstellen, dass U_C nur den Wert $-U_B$ annehmen darf. Also das macht für mich irgendwie keinen Sinn."

19 German original: "Man hat ja schon eine [Quelle] also für mich ist das einfach unlogisch. Warum sollte ich da noch eine einbauen? Ich kann das nicht erklären, aber für mich ist das einfach unlogisch... weil die erzeugt ja schon Spannung, warum soll die dann auch noch Spannung erzeugen? [...] U_B ist ja parallel zu U_C, dann wäre ja U_B gleich U_C und damit ist das denn ja eigentlich überflüssig sage ich mal, weil die dieselben Spannungen hätten."

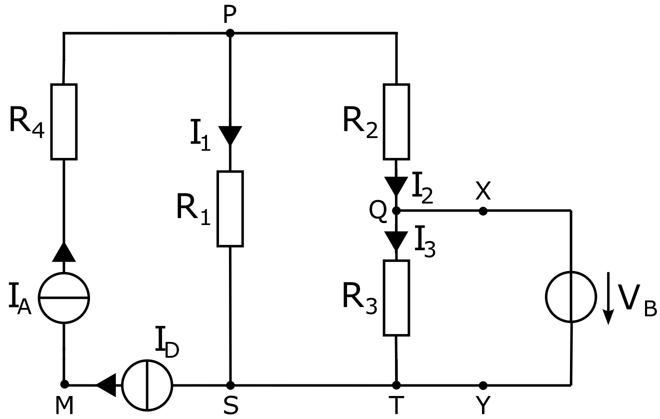


Figure 7.11: Variation of the circuit used in student interviews with a second current source (I_D) connected in series to the existing one (I_A). Original circuit shown in Figure 7.5.

7.3.2 *Current Sources in Series*

The interviews as described in Appendix F.

In the interviews, students were also asked if an ideal current source could be inserted into the circuit as shown in Figure 7.11. As one student remarked, this was a scenario that is usually not taught: "Sounds interesting. We never had that in our course!"[20]

Some students correctly stated that it was possible to insert the second current source, if both sources had the same value: "You can, but it must have the same value as I_A. Because it cannot be that 1 A flows here [at I_D] and 2 A here [at I_A]. Then, something would accumulate."[21]

One student, who correctly answered the question on the two parallel voltage sources, incorrectly assumed that the source currents would add up. Seemingly unsure of their answer, the student tried to apply the superposition principle but failed as this would have resulted in an open circuit in series with a current source: "If we think again with the superposition principle, this [I_D] would be an interruption in the wire and then I_A would be virtually cut off. So there could be no circuit here, nothing would flow at all."[22] The student concluded that it was not possible to place two current sources in series. As discussed on p. 128, it is not possible to apply the superposition principle to this situation. In the author's opinion, it is not necessarily expected of students to be aware of this limitation.

20 German original: "Klingt interessant. Das hatten wir nie in der Vorlesung!"

21 German original: "Kann man schon, aber die müsste den gleichen Wert wie I_A haben. Weil hier [bei I_D] kann ja nicht ein Ampere fließen und da [bei I_A] zwei Ampere. Das staut sich dann ja."

22 German original: "Wenn wir dann wieder mit dem Superpositionsprinzip denken, wäre das hier [I_D] eine Leitungsunterbrechung und dann hätte man I_A quasi ausgehebelt. Also dann könnte hier kein Stromkreis entstehen, dass überhaupt irgendwas fließt."

Nevertheless, many students revealed misconceptions regarding the behavior of current sources. The idea that the *source currents of current sources connected in series add up*, was stated several times. One student, for example, was unsure if the source currents would add up and made this a condition on their answer: "So if the current from a current source [in series] simply adds up [...], then one should not be allowed to do this. [...] If the currents are not added up, [...] then it wouldn't matter what value I_D had."[23] The student later indicated a preference for the correct answer: "But, since the current is always constant in the series connection, I would find it strange if one had a current source here, [...] where the current of I_D would be unequal to the current of I_A."[24]

Misconception: *Source currents of current sources in series add up*

Other students seemed to be more sure of the incorrect answer: "The two current sources add up – I think they add up – and if I [had] 2 A [before] and the currents are supposed to stay the same then I have to change I_A to 1 A for example and I_D to 1 A. In sum they have to stay the same."[25]

Like with voltage sources, the students in the interviews had trouble in their understanding of current sources. Many failed to understand that a current source *defines* the current going through it, and thus because of KCL two sources in series must have the same value. These problems with current sources, however, seem to stem from students' false belief that *sources increase the current through or voltage across them* instead of defining the current through or voltage across them.

Misconception: *Sources increase the current through or voltage across them*

When students used KCL, they correctly used it and seemed to grasp its implications to the distribution of current. This was different from KVL, where the problems seemed to stem from an incorrect understanding of voltage.

7.4 OPEN CIRCUITS AND OPEN SWITCHES[26]

The previous sections have presented multiple cases where students did not correctly apply KVL. Students incorrectly believed two bulbs

23 German original: "Also wenn sich die Ströme von einer Stromquelle [in Reihe] einfach so addieren [...], dann dürfte man das nicht. [...] Wenn die Ströme nicht addiert werden, [...] dann wäre es auch egal, welcher Betrag jetzt der Strom I_D hat."

24 German original: "Aber, weil in der Reihenschaltung der Strom ja eigentlich immer konstant ist, fände ich das komisch, wenn man hier eine Stromquelle hätte, [...] wo der Betrag von I_D ungleich dem Betrag von I_A wäre."

25 German original: "Die beiden Stromquellen addieren sich ja – ich denke das sie sich addieren – und wenn ich jetzt [vorher] zwei Ampere [hatte] und sage jetzt die Ströme sollen gleich bleiben dann muss ich I_A auf einen Ampere ändern zum Beispiel und I_D dann auf einen Ampere. Also in der Summe müssen die wieder gleich bleiben."

26 Parts of this study have been published in the proceedings of the REES conference in 2015 (Timmermann and Kautz, 2015b). Since then, several publications with data on open circuits and switches have been added, more than doubling the number of students reported on in this study. The analysis of possible student misconceptions has also been extended.

connected in parallel to a battery to be less bright than one bulb (see Section 7.1) or believed bulbs to change in brightness even though they were in parallel to a battery or voltage source (see Section 7.2). While students *should* have employed KVL to answer these problems, in many cases students argued based on current. This showed a preference for current-based reasoning and the inability to note contradictions with KVL, but it does not directly show that these students were in principle unable to correctly use KVL. Similarly, students who incorrectly answered questions about voltage sources connected in parallel (see Section 7.3) could just have difficulties with sources in general and not KVL in particular.

This section presents and compares different questions on the voltage across open circuits. These questions are of particular interest, as the voltage across an open circuit can only be determined using KVL. In contrast to resistive circuit elements, like bulbs, the voltage across an open circuit is not proportional to the current through it, which is zero by definition. The only other circuit element across which the voltage is neither fixed nor can be determined from the current, is the ideal current source. However, as shown in the previous section, many students seem to have difficulties with current sources. These difficulties influence students' answers about the voltage across them, making current sources unreliable elements for tests on KVL.

Open circuits are rarely used as elements in circuit diagrams. Thus, students might be confused when encountering them in a task. To circumvent this problem, the questions presented in the following use different circuit elements that behave as open circuits. In most cases, these are open switches, but one question also uses a socket whose bulb has been removed. In the following, the phrase 'open circuit' is used to refer to all of these cases, i. e. the voltage across an open switch as well as the voltage across an empty socket will be referred to as an open circuit voltage (V_{OC}).

It has been known for a long time that students often incorrectly assume the voltage across an open switch to be zero. Von Rhöneck (1982) reported on secondary school (grade 9) students' understanding of voltage. After instruction, 22 out of 26 students believed that the voltage across an open switch was zero. Other studies since then have also made observations on students' answers regarding open switches (Cohen et al., 1983; Picciarelli et al., 1991b,a; Engelhardt, 1997; Engelhardt and Beichner, 2004; Periago and Bohigas, 2005a; Hussain et al., 2012; Smaill et al., 2008; Smaill, 2009; Smaill et al., 2012). However, these observations were always in the context of other research questions. To the extent of the author's knowledge, no study has yet compared student answers on different tests and given an overview of what is known so far about student understanding of the open circuit voltage.

The following sections will contribute to fill this gap in the research. Section 7.4.1 presents the different questions that were used by different researchers to investigate students' beliefs on the voltage across an open switch. Section 7.4.2 gives an overview of the student answers that have been published for the different questions and that were gathered as part of this thesis. Section 7.4.3 compares the data from all sources to form a general result. Section 7.4.4 then presents four different misconceptions that have been suggested for the belief that the voltage across an open switch is 0 V and analyzes their frequency.

7.4.1 *Questions Used to Probe Student Understanding of Open Circuits*

To find questions that asked about the voltage across an open circuit or open switch, the archives of the American Journal of Physics, the IEEE Transactions on Education, the European Journal on Engineering Education, and Google Scholar were searched with the terms "open circuit" or "open switch" in combination with "student understanding" or "conceptual understanding". Moreover, the publications of the American Society for Engineering Education were searched for the terms "open circuit" or "open switch" in combination with "understanding". Additionally, relevant concept inventories listed in a database of the Engineering Education Research Group (EERG) at TUHH were searched for questions on open circuit voltage. The references of all sources found were searched for additional questions.

Four different questions were identified that

- asked about the voltage or change of voltage across an open circuit or open switch, possibly also across circuit elements in series with the open circuit/switch.
- contained data on students' answers for at least the correct answer as well as the answers that there is no voltage across an open switch ($V_{OC} = 0\,V$).
- tested students at university level.

These questions are presented in the following.

7.4.1.1 *Open Circuit Question 1: DIRECT Test by Engelhardt*

In 1997, Engelhardt published the DIRECT, a concept inventory that tests students' understanding of resistive DC circuits and contains several questions with open switches. One of these questions, question number 28, asks for the voltage across an open switch plus a bulb in series with it. The question from version 1.0 of the DIRECT is reproduced in Figure 7.12. Version 1.1 of the test also contained this question, but added the answering option *none of the above*. Engelhardt remarked that "this change did not significantly affect the distribution of answers. However, a better alternative may be either 4 V or 8 V. Students may assume that the switch has the same resistance as each of the two bulbs" (p. 151). A question discussed later (Figure 7.17 and Table 7.16 on p. 154) indicates that this concern might not be warranted. The question offered students to select the explanation "a third of the voltage drops at each of the bulbs and the switch, respectively." This explanation was selected by fewer students (8%) than the option *none of the above* offered by Engelhardt (7% to 14% as shown in Table 7.10, p. 141).

As shown in Figure 7.12, the question asks for V_{AB}, the voltage across the open switch *and* one of the the bulbs. However, in the author's experience virtually all students seem to know that a bulb with no current has no voltage. Thus it is reasonable to assume that students who believe V_{AB} to be zero, also believe the voltage across the open switch to be zero. Similarly, it seems reasonable to assume that students who believe V_{AB} to be 12 V also believe the voltage across the open switch to be 12 V.

The DIRECT has been adapted to fit different needs. Goris (2012) used the test and thus the question discussed here as a basis for student interviews. Sabah (2007) developed the DIRECT-TTC, a two-tier version of the DIRECT. His test contained a modified version of the question discussed here. It asked for the voltage across only the open switch. Consequently, students were only given the three answering options (a) 0 V, (b) 12 V, and (c) "less than 12 V" (Sabah, 2007, p. 130). As Sabah had developed a two-tier test, students were also given five explanations to select from. The last of which was "Others (please specify)". Since no student data on Sabah's test were published, the question from that test is not included in this study.

7.4.1.2 *Open Circuit Question 2: Two-Tier Multiple-Choice Question by Hussain et al.*

Hussain et al. (2012) reported on an investigation of student misconceptions about open and short circuits. In their research, they used the question shown in Figure 7.13, a derivation of the modified DIRECT-TTC question from Sabah (2007). Hussain et al. neither

28) What is the potential difference between points A and B?

(A) 0 V
(B) 3 V
(C) 6 V
(D) 12 V

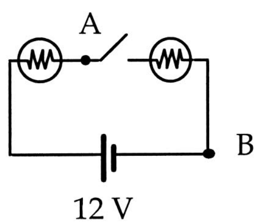


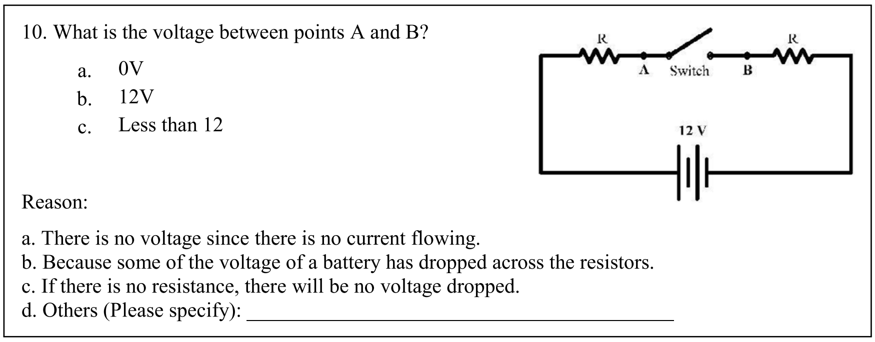
Figure 7.12: Open circuit question 1. This is question 28 in the DIRECT, version 1.0 (Engelhardt, 1997). Reproduced with permission.

changed the phrasing of the question nor the answering options from Sabah. They did, however, remove one explanation for students to select and rephrased other explanations.

In theory, the addition of explanations in two-tier multiple-choice questions increases the number of options for students to select from. With n answering options and m possible explanations, there are theoretically $n \cdot m$ possible combinations. In practice, however, explanations often are phrased so that they only fit one or two answers. Consequently, two-tier questions that have not been designed carefully enough often only provide n options after answer-explanation combinations have been eliminated that make no sense based on pure logic.

Two-tier multiple-choice questions are introduced in Section 5.3.3 (p. 67).

The question shown in Figure 7.13 is in the author's opinion a question that only has a few answer-explanation combinations that make sense logically. Unfortunately, the combinations provided in this question increase the difficulty of the question by making the correct combination of answer and explanation *seem to be* incorrect, independent of the physics of the question. Explanations *a* and *c* contain the phrase "no voltage". Thus, they must be explanations for answer *a* (0 V). Explanation *b* contains the phrase "some of the voltage [...] has dropped", and thus only fits answer *c* ("less than 12"). There are two factors that might influence students to select the incorrect answer *a* (0 V). On the one hand, the missing unit in answer *c* ("less than 12") makes this answer technically incorrect, and on the other hand, only with answer *a* (0 V) students have to make a second decision for their explanation. When selecting the correct answer *b* (12 V), students can, based on the phrasing of the question, only select explanation *d* "Others (Please specify)". It is quite unusual that the correct answer or explanation is not given as a "normal" multiple-choice option and a test taker has to fill in the correct answer by themself. In the author's opinion, unless students were used to the correct answer or explanation being such an option, most students would not assume it to be the correct one. Thus, it is likely that the results of this question are skewed to answer *a* (0 V), resulting in less correct answers.


10. What is the voltage between points A and B?

a. 0V
b. 12V
c. Less than 12

Reason:

a. There is no voltage since there is no current flowing.
b. Because some of the voltage of a battery has dropped across the resistors.
c. If there is no resistance, there will be no voltage dropped.
d. Others (Please specify): ______________________

Figure 7.13: Open circuit question 2, used by Hussain et al. (2012). Reproduced with permission from Elsevier.

7.4.1.3 *Open Circuit Question 3: Removed Bulb by Cohen et al.*

A third question, shown in Figure 7.14a, was published by Cohen et al. (1983). This question has two important differences to the two previous questions. Firstly, it does not ask students about a voltage but rather about a change in voltage. Secondly, it does not use an open switch, but instead a socket whose bulb is removed. Both aspects likely increase the difficulty of the question. They require students to compare two different states (with the bulb inside its socket and with the bulb removed from its socket) and to have additional factual knowledge (the electrical properties of a socket with no bulb in it).

The question by Cohen et al. (1983) was modified by Periago and Bohigas (2005a) as well as by the author of this thesis. While the three different versions of the question (Question 3, Question 3a, and Question 3b) change the way the question is phrased and even the circuit layout, the core idea remains the same. The original question as well as its variants are shown in Figure 7.14.

Question 3 by Cohen et al. (1983) is a multiple-choice question that has four answering options. These address two different physical quantities. Answer *a* is a statement about bulb M, the bulb that is not removed, while answers *b*, *c*, and *d* are statements about the voltage across the socket of the removed bulb.

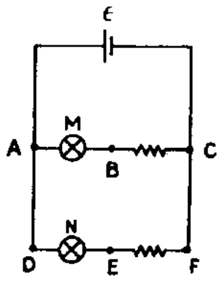
Question 3a by Periago and Bohigas (2005a) uses the same circuit with slightly different symbols. The question does not explicitly address that the battery is ideal, i. e. has no internal resistance. It is, however, likely that in the course investigated by Periago and Bohigas all batteries were considered ideal. If that was the case, students would likely still have assumed the battery to be ideal. The question is also changed from multiple-choice to free-response, with the two different physical quantities that can be addressed in the multiple-choice answers split into two independent questions.

Question 3b was developed as part of this thesis and not only uses slightly different symbols, but also a modified circuit. The resistors are replaced with bulbs and a third parallel branch with only one bulb was added. These changes likely do not significantly affect the difficulty. The resistors that were replaced with bulbs only had the function of an unspecified load and the third branch has the same effect as the other branch whose bulb is not removed. As this new branch is added "behind" the branch in which the bulb is removed, students who use localized reasoning will likely not consider the third branch in their answer. Question 3b is part of a larger task that asks students several questions regarding the same circuit. Initial questions ask students to compare the brightness of individual bulbs, allowing them to familiarize themselves with the circuit. In task 1.4 (not shown in Figure 7.14c), students are asked about the change of the voltage between X and Y, i. e. the voltage across bulb C when bulb D is removed from its socket. While the additional branch might make this question

The full test is presented in Appendix E.11 (p. 424).

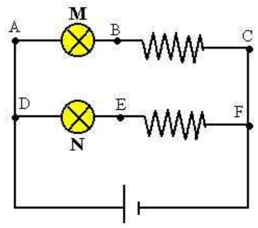
3. *The voltage source ε in the figure has no internal resistance. Both bulbs M and N are lit. N is removed from its socket. Consequently:*

a. The bulb M will light more strongly.
b. The p.d. between D and E will become zero.
c. The p.d. between D and E will not change.
d. The p.d. between D and E will increase.



(a) Question 3, reproduced from Cohen et al. (1983) with the permission of the American Association of Physics Teachers.

Q9. We have a circuit made up of a battery, two light bulbs M and N, and two resistors. If we disconnect light bulb N and put nothing in its place, explain:



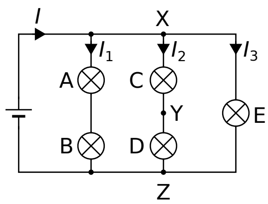
a) How will the potential difference vary between points D and E?

b) How will the brightness of bulb M change?

(Comment on the variations regarding the first situation, when bulb N was still connected).

(b) Question 3a, by Periago and Bohigas (2005a). Licensed CC-BY-NC.

Problem 1 (8 points)
The battery in the circuit at right can be treated as an ideal voltage source. The long line indicates the positive terminal of the battery. All five bulbs are identical and all occurring voltages are within the operating range of the bulbs.



Task 1.1 (1 point)
Bulb A glows…

Task 1.1	A	B	C	D	E
	brighter than B	less bright than B	equally bright as B		

Now, bulb D is removed from its socket.

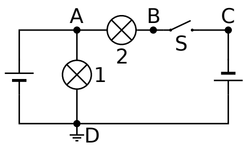
Task 1.5 (1 point)
The absolute value of the voltage between nodes Y and Z, $|U_{YZ}|$,…

Task 1.5	A	B	C	D	E
	increases,	stays the same,	decreases to 0,	decreases, but not to 0.	

(c) Question 3b, developed as part of this thesis.

Figure 7.14: Different variations of open circuit question 3.

1. The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery. The symbol at node D denotes zero potential. The bulbs 1 and 2 are also identical. Switch S is open at first.



Open switch:

a. Rank the three voltages V_{AB}, V_{AC} and V_{AD} by their absolute value. Use the relational operators '>', '<' and '='. State explicitly, if two voltages are equal or a voltage is zero.

Answer:

Reasoning:

Figure 7.15: Open circuit question 4, developed as part of this thesis.

more difficult than the versions presented above, students might also have had an advantage as the questions on other aspects of the circuit might have helped them in understanding it better.

7.4.1.4 *Open Circuit Question 4: Ranking Question by Timmermann*

The fourth question, shown in Figure 7.15, is a ranking question that is a pre-test to a Tutorial and was designed by the author of this thesis. The design decisions that went into this question are detailed in Section 9.6.4 that describes the design of the whole Tutorial. As described there, the same circuit has been developed independently by Smith and van Kampen (2011) for the use in their Tutorial worksheets.

7.4.2 *Published Student Data*

Most of the questions shown above have been used by multiple researchers at different institutions. This section contains an overview of the published data for each question.

All four questions described above have two common answering options: the correct answer, and the answer $V_{OC} = 0\,V$, i. e. zero voltage across the open circuit. The other answering options vary per task and in some cases include answers that are unrelated to V_{OC}. To allow for a fair comparison of the answers to the different questions, only students who made a statement about the voltage across the open circuit in the respective question were included in the following evaluation. Answers corresponding to an answering option not related to that voltage as well as blank answers were removed. As some answers were excluded, the percentages reported in the following can differ in some cases from those shown in the cited sources. The following investigation shows the beliefs about open circuit voltage among students *who made a statement about said voltage when asked*.

Table 7.10: Student answers to open circuit question 1, question 28 of the DIRECT by Engelhardt (1997).

		Answer				
Cohort	N	0 V	3 V	6 V	12 V	none of the above
Engelhardt (1997)						
v. 1.0, High school	440	46 %	6 %	27 %	21 %	
v. 1.0, University	674	64 %	0 %	14 %	22 %	
v. 1.1, High school	248	45 %	5 %	15 %	20 %	14 %
v. 1.1, University	428	45 %	2 %	18 %	28 %	7 %
Smaill et al. (2008); Smaill (2009); Smaill et al. (2012)						
v. 1.0, 2007	560	44 %	*n/a*	*n/a*	26 %	
v. 1.0, 2008	543	45 %	*n/a*	*n/a*	24 %	
v. 1.0, 2009	577[a]	39 %	*n/a*	*n/a*	25 %	
Timmermann (this study)						
v. 1.1, EE1ME 2017, instr. B	278	64 %	0 %	10 %	26 %	1 %
v. 1.1, EE1ME 2018, instr. B	198	72 %	0 %	6 %	22 %	1 %
v. 1.1, EE1ME 2019, instr. C	185	62 %	1 %	12 %	25 %	0 %

a Read from Fig. 1 in Smaill et al. (2012).

7.4.2.1 *Data on Open Circuit Question 1*

Data on the first question is available from three different sources and summarized in Table 7.10.

DATA FROM ENGELHARDT Engelhardt (1997) gathered student answers to analyze versions 1.0 and 1.1 of the DIRECT. Answers to the question investigated here are shown in Table 7.10. Engelhardt reports that all students tested by her had completed instruction on direct current electric circuits prior to answering the question and were all attending high school or university in the United States, Canada, or Germany (p. 69f.). The distribution of answers is fairly consistent for both levels of education and both versions of the test. However, comparing this question to the other 28 questions in the test, the question was abnormally difficult, disproportionally so for students who were weak in the whole test.

DATA FROM SMAILL ET AL. In three different papers (Smaill et al., 2008; Smaill, 2009; Smaill et al., 2012), Smaill reported on question 28 from version 1.0 of the DIRECT that was given to students as part of a larger test at the University of Auckland. That test was administered to first semester students at the start of an introductory course on electrical and digital systems in 2007, 2008, and 2009. Smaill et al. (2012)

suspect that "many students enrolled in [that course] have no particular interest in matters of an electrical nature and may not have studied this aspect of physics in high school". Only about a quarter of the students enrolled in the course later pursue a degree in electrical and computer engineering. Smaill et al. only reported the absolute number of students participating in the test and the percentages for the answers 12 V and 0 V. Therefore, the percentages for the answers 3 V and 6 V are given as *n/a* in Table 7.10 and the percentage of blank answers is not known. Consequently, the percentages for the 12 V and 0 V answers could not be adjusted to be only based on non-blank answers. As version 1.0 of the DIRECT was used, the answering option *none of the above* was not part of the test.

The full tests are shown in Appendecies E.24 (p. 472) and E.26 (p. 480).

TIMMERMANN (THIS STUDY) Version 1.1 of the question from Engelhardt was also used in two quizzes in the course EE1ME in week 4 in 2017 and in week 5 in 2018. Students in this course had participated in one or two Tutorials on the topics of *Current and Resistance* as well as *Voltage*. To match the style of the rest of the test, a brief problem-setup was added to the task, stating "the circuit below contains two identical bulbs, a 12 V battery, and a switch (open)". In addition to their multiple-choice answer, students were asked to give a detailed explanation of their answer in the 2017 test. The 2018 test did not ask students to explain their answers. About half of the students in that test received an alternate version of the question in which the circuit was rotated 90 deg clockwise, so that point A still was above point B. Since there was no significant difference in the answers to these two versions of the test, they are not shown separately in Table 7.10

7.4.2.2 *Open Circuit Question 2: Two-Tier Multiple-Choice Question by Hussain et al.*

Open circuit question 2 was used only by Hussain et al. (2012), once before and once after an unspecified intervention. The percentages of student answers were reported for 4 of the 12 possible answer-explanation combinations. These were selected by 83% and 87% of the 47 participants in the pre-test and post-test, respectively. It is unclear if the remaining students did not select any answer or if they selected answer-explanation combinations not reported in the paper. The answers not reported were assumed to be blank and thus removed. This assumption being false would result in an overestimation of the correct and an underestimation of the $V_{OC} = 0\,V$ answer. The distribution of answers for both tests is reported in Table 7.11.

Table 7.11: Student answers to open circuit question 2.

		V_{OC}		
Test	N	0 V	less than 12 V	12 V
Pre-test	39	79 %	21 %	0 %
Post-test	41	68 %	27 %	5 %

7.4.2.3 *Open Circuit Question 3: Removed Bulb by Cohen et al.*

Student answers for open circuit question 3 are available from several sources, one of which used question variant 3a, another used variant 3b. The available data is listed in Table 7.12.

DATA FROM COHEN ET AL. Cohen et al. (1983) administered their test to 145 high school students and 21 high school teachers from Israel. The majority of students (96) was in grade 12, which Cohen et al. compare to first year college in the United States. Additional 22 students were in grade 11 and further 27 in grade 9. The students in grade 9 were described as "gifted" and had the highest average test score. The average test score of the students in grade 11 was significantly below that of the students in grade 12. All students had completed instruction on DC circuits prior to taking the test.

The first two rows of Table 7.12 show students' and teachers' answers as reported by Cohen et al. (1983). As described above, answers that were blank or did not relate to the voltage across the open circuit are excluded. For the data reported by Cohen et al., this affects 36 students and 4 teachers who selected answer option *a*, "the bulb M will light more strongly" (see Figure 7.14a).

DATA FROM PICCIARELLI ET AL. Open circuit question 3 was also used in a test by Picciarelli et al. (1991a,b). They administered their test to two samples of university students in Italy. The participants in Sample 1 were in their second year at University. This group was tested twice, once "before being taught the topics on circuitry" (Picciarelli et al., 1991b, p. 58), and once after instruction. As this group contained 88 electrical engineering students, it is possible that they had prior knowledge on electrical engineering, even though Picciarelli et al. do not mention it. Their second sample consisted of 63 students enrolled in physics and electrical engineering who were in their third year, had passed the exams in the second year, and "had participated in laboratory sessions and teaching courses on electronics at quite a high level" (Picciarelli et al., 1991a, p. 42).

The data reported by their study is also listed in Table 7.12. As with the data from Cohen et al. (1983), the students that selected answering option *a* are not included in the dataset.

Table 7.12: Student answers to open circuit question 3.

		voltage across socket when bulb is removed			
Source	N	increases	stays the same	becomes 0	decreases
Cohen et al. (1983)					
Teachers	17	5 %	59 %	36 %	
Students	109	13 %	27 %	60 %	
Picciarelli et al. (1991b,a)					
Sample 1, pre-test	104	33 %	45 %	22 %	
Sample 1, post-test	46	22 %	43 %	35 %	
Sample 2	45	32 %	44 %	24 %	
Periago and Bohigas (2005a)					
Students	94	3 %	44 %	53 %	
Timmermann (this study)					
Students in EE1ME	484	12 %	16 %	62 %	10 %

DATA FROM PERIAGO ET AL. Periago and Bohigas (2005a,b) used the modified question 3a. Their study investigated 184 Italian university students who had already passed all courses in the first half of their degree programs, including a course on electromagnetism, and had also been taught DC circuit analysis in the last two years of their secondary school education.

Their question, reproduced in Figure 7.14b, has the same problem set-up as the question from Cohen et al. (1983). While their question is open-ended, Periago and Bohigas (2005a) asked students to make a statement about the brightness of the remaining bulb *as well as* the voltage across the removed bulb's socket. They then coded students' answers into a matrix of 3 categories for the voltage between D and E and 2 categories for the brightness of bulb M. For the data in Table 7.12, the two categories of answers for bulb M were combined. The answers categorized as "not cataloguable" are not included in Table 7.12. Periago and Bohigas remarked that only when the not cataloguable answers are ignored, their data becomes similar to those from Cohen et al. (1983).

The full test is presented in Appendix E.11 (p. 424).

TIMMERMANN (THIS STUDY) The same concept for a question was used in form of question 3b (see Figure 7.14c) in an exam in EE1ME at TUHH. The versions of the question presented above provided answering options concerning the change of voltage across the socket of the bulb as well as the brightness of the bulb that was not removed. In contrast, this version only asks about the change of voltage across the socket. Since in all versions of this question only answers regarding the voltage across the empty socket were counted, the percentages of each test add up to 100%. Unlike the previous questions, which offered only the answering options that the voltage *increases*, *stays the same*, and *becomes zero*, this question also offers the answering option that the voltage *decreases, but not to zero*.

7.4.2.4 *Open Circuit Question 4: Ranking Question by Timmermann*

Open circuit question 4 was developed as part of this study and thus only given to students as part of this study. Overall, the test was administered 7 times. In each case, students had participated in instruction on KCL, KVL, and Ohm's Law, but not worked on the Tutorial described in Chapter 9, which uses this question as a pre-test.

The full tests are shown in Appendices E.10 (p. 420), E.12 (p. 428), E.15 (p. 440), E.16 (p. 444), E.19 (p. 456), E.22 (p. 468), and E.26 (p. 480).

The question asks students to rank the voltages V_{AB}, V_{AC}, V_{AD}, and V_{BC} by their absolute value and indicate if one or more of these voltages is zero. Most students indicated a voltage being zero by including 0 V in their ranking, while some only did so as part of the explanation of their answer. In the later case, students' rankings were modified to include 0 V. As the voltage V_{AB} is across a bulb that quite obviously does not glow, all students should have included 0 V in their ranking.

Table 7.13 provides an overview of different statements that relate to the voltage across the open switch. These are $V_{BC}>0$, the correct statement about the voltage across the open switch, $V_{BC}=0$, the incorrect statement that there is zero voltage across the open switch, $V_{AB}=V_{AC}$, which can only be true if V_{BC} is zero, and $V_{AC}=0$, which

Table 7.13: Percentage of students that made specific statements when answering open circuit question 4. N is the number of students that participated in the test. For each statement, two numbers are listed: the number of students who used the respective voltage(s) in their ranking as well as the percentage of these students that actually stated the respective relation.

				Correct	Incorrect Statements		
Course	Year	Week	N	$V_{BC} > 0$	$V_{BC} = 0$	$V_{AB} = V_{AC}$	$V_{AC} = 0$
EE1ME	2013	11	310			69 % of 289	51 % of 291
	2014	6	139	2 % of 91	49 % of 91	48 % of 85	44 % of 88
	2015	4	275	2 % of 178	58 % of 178	58 % of 178	54 % of 188
	2016	4	286	13 % of 245	64 % of 245	56 % of 236	56 % of 239
	2018	5	201	4 % of 188	60 % of 188	63 % of 188	55 % of 189
	2019	4	194	6 % of 170	61 % of 170	52 % of 165	53 % of 167
EE1UK	2016	3	125	2 % of 108	82 % of 108	91 % of 108	79 % of 109
EE1EE	2015	6	200			48 % of 149	33 % of 156

means that V_{BC} is zero when there is zero voltage across bulb B. For each statement the number of students who used the voltages of that statement in their ranking is listed in the table. Also listed is the percentage of students who actually made that statement. If students included all voltages as well as zero in their rankings and correctly applied KVL, the numbers in these columns would be the same in every row. Due to incomplete and blank rankings, this number often is considerably lower than the number of students who participated in the test.

A sizable fraction of students did not indicate any voltage to be zero. In the test in EE1ME in 2014 (row 2 in Table 7.13) for example, 139 students participated in the test, but only 91 used the voltage V_{BC} in their ranking. Of these, 2% stated $V_{BC}>0$ and 49% stated $V_{BC}=0$. The remaining 49% of students used V_{BC} in their ranking, but did not relate it to 0 V. It is tempting to assume that these remaining students believed V_{BC} to be larger than zero. After all, the task asked them to indicate if a voltage was zero. However, most of these students did not include 0 V in their ranking at all, when one would assume they would at least identify the voltage V_{AB} across the open-circuited bulb to be zero. Still, as these students did not indicate $V_{BC}=0$, they are not counted as such.

Two of the tests shown in Table 7.13 did not ask for V_{BC}. The test in 2013 in EE1ME did not do so, because it was initially assumed that the number of students who believed $V_{BC}=0$ V could be deduced from students' statements about V_{AB} and V_{AC}. As described above, however, students' answers proved to be too inconsistent or not based on KVL. Thus, later versions of the test also asked students to include V_{BC} in their ranking. The test in 2015 in EE1EE contained an incorrect phrasing of the question. Students were asked for V_{CD} instead of V_{BC}.

Student answers for the incorrect statements $V_{AB}=V_{AC}$ and $V_{AC}=0$, still allow for a comparison of these two cohorts with the other five. The 2013 EE1ME cohort seems to be largely similar to the other EE1ME cohorts, although the statement $V_{AB}=V_{AC}$ is made more often than usual. One reason for this discrepancy might be a change in difficulty of the questions, as students were not explicitly asked for V_{BC}, the voltage relating V_{AB} to V_{AC}. Students in the course EE1EE performed better than virtually all of the other cohorts. The task might be considered easier, as students were asked for the voltage V_{CD}, which might help them realize that all voltages can be determined through the batteries. Additionally, it is plausible that students in a course for electrical engineers perform better than those in a course for non-electrical-engineers.

7.4.3 *Comparison of Available Data*

While the four questions are different in multiple ways, they all contain the answering option $V_{OC} = 0\,V$, i. e. there is no voltage across an open circuit, and a correct answer. The specifics of the correct answer differed between the questions. Table 7.15 gives an overview of the different cohorts presented above and the percentages of students who answered $V_{OC} = 0\,V$ or gave the *correct* answer.

The table lists data from 22 tests in which overall 6107 students participated. Not counted are students who gave an answer not related to the open circuit question or gave no answer at all. Four cohorts participated in two tests: The 2018 and 2019 EE1ME courses were both given Question 1 and 4, Hussain et al. (2012) used Question 2 as a pre- and a post-test in the same course, and Question 3 was given twice to Sample 1 from Picciarelli et al. (1991b). For the average listed in Table 7.15, the two tests of each cohort were weighted by ½. Therefore, the number of students listed at the bottom of Table 7.15 is 5607.

While there is some variation in the percentages of correct answers, the number of students who stated $V_{OC} = 0\,V$ is fairly consistent. These differences and similarities can be more easily analyzed when the results for each test are averaged per question, as was done in Table 7.14.

In Table 7.14, the questions are ordered by the percentage of correct answers. Inversely, the number of $V_{OC} = 0\,V$ answers increases from top to bottom. This order can likely be explained by the difficulty of the different questions. Question 1 is the least complex question and has the highest percentage of correct answers. It is followed by Question 3, which is more difficult as two states have to be compared and knowledge about bulb sockets is required. Questions 2 and 4 have the lowest percentages of correct answers. These low percentages are likely due to the correct answer being paired with the explanation "Other (please specify)" for Question 2 and the complexity of the circuit for Question 4.

Based on the Tukey test (Montgomery, 2001), there is no significant difference between the average number of students believing

Table 7.14: Data from Table 7.15 averaged per question. Question 3 includes versions 3a and 3b.

Question	N	$V_{OC} = 0\,V$	correct
1	4135	51 %	24 %
3	912	52 %	16 %
4	980	62 %	6 %
2	80	73 %	3 %

Table 7.15: Frequency of the belief that the voltage across an open switch is zero. Listed is data about high school or university students who have not had instruction focusing especially on the voltage across open switches.

Question	Study & Cohort	N[a]	$V_{OC} = 0\,V$	*correct*
1	Engelhardt (1997)			
	USA, test v. 1.0, high school, after instruction	440	46 %	21 %
	USA, test v. 1.0, university, after instruction	674	64 %	22 %
	mostly USA, test v. 1.1, high school, after instruction	248	45 %	20 %
	mostly USA, test v. 1.1, university, after instruction	428	45 %	28 %
	Smaill et al. (2008, 2012); Smaill (2009)			
	New Zealand, test v. 1.0, university, 2007, 1st semester, before instruction	560	44 %	26 %
	New Zealand, test v. 1.0, university, 2008, 1st semester, before instruction	543	45 %	24 %
	New Zealand, test v. 1.0, university, 2009, 1st semester, before instruction	577	39 %	25 %
	Timmermann (this study)			
	Germany, course EE1ME, 2017, instructor B, week 4, 1st & 3rd sem. eng., after trad. instruction	278	64 %	26 %
	Germany, course EE1ME, 2018, instructor B, week 5, 1st & 3rd sem. eng., after trad. instruction[b]	198	72 %	22 %
	Germany, course EE1ME, 2019, instructor C, week 4, 1st & 3rd sem. eng., after trad. instruction[c]	185	62 %	25 %
2	Hussain et al. (2012)			
	Malaysia, university, start of 2nd semester, after 1 semester of instruction[d]	39	79 %	0 %
	Malaysia, university, end of 2nd semester, after 2 semesters of instruction[d]	41	68 %	5 %

3	Cohen et al. (1983)			
	Israel, high school up to 1st year college equivalent, mostly after instruction	109	60 %	13 %
	Picciarelli et al. (1991a,b)			
	Italy, university, sample 1, 2nd year, before instruction[e]	104	22 %	33 %
	Italy, university, sample 1, 2nd year, after instruction[e]	46	35 %	22 %
	Italy, university, sample 2, 3rd year, after instruction	45	24 %	32 %
3a	Periago and Bohigas (2005a)			
	Italy, university, 4th year on electromagnetism	94	53 %	3 %
3b	Timmermann (this study)			
	Germany, course EE1ME, exam 2013, 1st & 3rd semester engineering with some Tutorials	484	62 %	12 %
4	Timmermann (this study)			
	Germany, course EE1ME, 2014, instructor A, week 6, 1st & 3rd sem. eng., after trad. instruction	91	49 %	2 %
	Germany, course EE1ME, 2015, instructor A, week 4, 1st & 3rd sem. eng., after trad. instruction	178	58 %	2 %
	Germany, course EE1ME, 2016, instructor A, week 4, 1st & 3rd sem. eng., after trad. instruction	245	64 %	13 %
	Germany, course EE1ME, 2018, instructor B, week 5, 1st & 3rd sem. eng., after trad. instruction[b]	188	60 %	4 %
	Germany, course EE1ME, 2019, instructor C, week 4, 1st & 3rd sem. eng., after trad. instruction[c]	170	61 %	6 %
	UK, course EE1UK, 2017, week 1, 3rd sem. eng., before instruction	108	82 %	2 %
	All studies	5607	52 %	20 %

a Students who made a statement about the voltage across the open circuit in the respective question.
b, c, d, e Only counted half, as the cohort participated in two tests.

$V_{OC} = 0\,V$ for the questions. The average number of correct answers, however, for Questions 1 and 3 is significantly different from that for Questions 2 and 4.

Two further observations on the data in Table 7.15 are noteworthy: On average, 52% of students stated that there would be no voltage across an open circuit. This is a huge fraction of students, who not only answer incorrectly, but who give one specific incorrect answer that strongly suggests a fundamental error in their understanding of voltage. Furthermore, this high average is not the result of some outliers. Even in the "best" population (Picciarelli, Sample 1 before instruction), more than every fifth student believes $V_{OC} = 0\,V$, in the "second best" population (Picciarelli, Sample 2), about every fourth student believes $V_{OC} = 0\,V$, and in all other 20 populations at least every third student believes $V_{OC} = 0\,V$.

In the five-bulbs test, reported upon in Section 7.1, the engineering students at TUHH and Loughborough University performed better than the Physics students tested by McDermott (2001). In the different questions on open circuits, in contrast, the engineering students at TUHH and Loughborough University on average performed worse than the other cohorts. The reason for this is unknown.

While the percentages of students believing $V_{OC} = 0\,V$ might seem to have quite a wide spread, the larger cohorts are closer to the average. This can be easily seen in Figure 7.16, which contains one data point per cohort. The horizontal position of a data point indicates the percentage of students of its cohort who believe the voltage across the open circuit to be zero ($V_{OC} = 0\,V$), while the vertical position indicates the number of students in that cohort. While the data points below $N = 200$ have quite a large spread, the data points above that value are much closer to the average.

Figure 7.16 will be used as a baseline for students' understanding of the voltage across open switches in the evaluation of the Tutorial *Potential*, which is presented in Chapter 9.

7.4.4 *Proposed Misconceptions*

More than half of the students who made a statement about the voltage across the open circuit in one of the questions shown above believed the voltage to be zero. Different researchers have proposed different misconceptions that could explain this belief. In this section, the different misconceptions will be presented and, when possible, illustrated using quotes from students.

Misconception: *Voltage is a property of current*

If voltage were a property of current, it would only be defined at places where current is. In one of the interviews described in Appendix F, a student stated for example: "voltage is actually kind of the

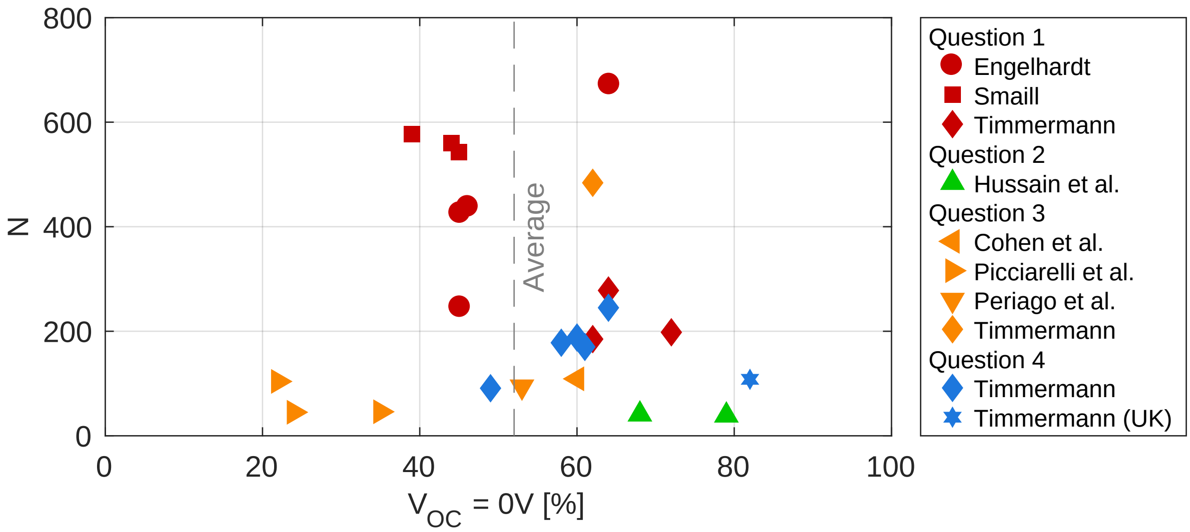


Figure 7.16: Visualization of the data in Table 7.15. Frequency of the belief that the voltage across an open circuit or open switch is zero for different cohorts and questions. The vertical axis indicates how many students in the respective cohort answered the questions. The horizontal axis indicates the percentage of students who gave the answer 0 V.

speed and current the number of electrons."[27] This student's mental model of current is very similar to the one taught: Current is the amount of charge, which can be measured as number of electrons that pass through a given area, e. g. cross section of a wire. The student's mental model for voltage, however, does not align with the model taught. The student believes voltage to be the speed of electrons, while in the scientifically accepted model voltage has the unit *energy per charge*. It is the energy a charge gains when it moves from one point to another. This energy is not a property of the charge, but of the system that this charge is part of. The charge used in this definition is fictitious and does not exist in the real system. In the student's mental model, in contrast, there cannot be voltage without current, as there would be nothing that could have the property of speed. Thus, asking for the voltage across an open switch is not a valid question. As there are no electrons crossing an open switch, one would be asking for the speed of non-existent electrons.

Another example of this line of reasoning can be found in *Merriam-Webster's Advanced Learner's English Dictionary*, which defines voltage as "the force of an electrical current that is measured in volts" (Merriam-Webster, 2008). In this definition, force would be a property of current. Without current, there would be nothing to exert the force called voltage.

Von Rhöneck (1982) first proposed that students might believe that voltage is a property of current and later (2008) added that "the volt-

27 German original: "Spannung ist ja eigentlich sozusagen die Geschwindigkeit und Strom die Anzahl der Elektronen."

age concept is one of the most abstract concepts introduced in a secondary-school physics course. Usually students do not develop an independent voltage concept, but interrelate it to the concept of electric current. That means voltage is seen as a property of the electric current". Engelhardt (1997, p. 93) agrees with von Rhöneck that students have trouble distinguishing between current and voltage. However, she suggests two other explanations: *either* voltage is caused by current *or* voltage and current always appear together.

Misconception: *Voltage is caused by current*, or *voltage and current always appear together*

If voltage were not a property of current, but produced by it, voltage could be defined at points where there is no current. It would, however, be zero in circuits where no current flows. On the other hand, the misconception that voltage and current always appear together removes any causality between the two quantities and reduces their relationship to the observation that "when there is one, there is the other" (Engelhardt, 1997, p. 93). While there certainly is a logical difference between the two misconceptions, they are difficult to distinguish in students' explanations.

When answering Question 1, a student at TUHH argued "Switch is open. This means that there is no circuit and no voltage."[28] However, the student wrote the German "Stromkreis", which is usually translated as *circuit*, but translated literally means *current loop*. It is possible the student intentionally used current *and* voltage in his answer, stating that "there is no current and no voltage". While that might be an over-interpretaion, there are many students who believe the voltage across the open switch to be zero and explain their answer by stating that "There is no current in the loop with the switch."[29]

Misconception: *Voltage is a substance that moves through the circuit*

In interviews conducted using questions from the DIRECT, Goris (2012) observed students that thought of "voltage as a matter/substance that circulated inside of the circuit. If there is an open switch, there is no voltage in the elements after the switch" (p. 164). When answering Question 1 (Figure 7.12), a student at TUHH for example reasoned "There is a 12 V battery which supplies voltage, but the circuit is open. The voltage goes out, but does not return to the battery via path A B."[30] Another student at TUHH ranked the voltages in Question 4 (Figure 7.15) as $V_{AB}=V_{AD}>V_{AC}=V_{BC}=0\,V$ and explained "The voltage is divided between bulbs 1 and 2, thus V_{AD} is equal to V_{AB}. V_{AC} is 0, as there is a gap."[31] This student believed that there is voltage up to the open switch, but as Goris (2012) puts it, they believed that "there is no voltage in the elements after the switch" (p. 164).

28 German original: "Schalter ist offen. Damit herrscht kein Stromkreis und keine Spannung liegt an."

29 German original: "In der Masche mit dem Schalter fließt kein Strom"

30 German original: "Es gibt zwar eine 12 V Batterie, die Spannung abgibt, jedoch ist der Stromkreis offen. Die Spannung geht zwar raus, aber kommt nicht wieder über den Weg A B bei der Batterie an."

31 German original: "Die Spannung teilt sich zwischen Lampen 1 und 2 auf, daher ist U_{AD} und U_{AB} gleich groß. U_{AC} ist 0, da es eine Unterbrechung gibt."

Skromme and Robinson (2015) argued students could think that "No voltage can exist across an open circuit because there is no current flow. This idea probably results from a naïve application of Ohm's law to the situation, without realizing that the R in question is infinite". This misconception had previously been suggested by Smaill et al. (2012), who called it "a blind reliance on Ohm's law", as well as Hussain et al. (2012), Picciarelli et al. (1991b), and Periago and Bohigas (2005a).

Misconception: *Ohm's law applies to open circuits*

An example for this misconception might be the following explanation given by a student answering Question 4 (Figure 7.15, p. 140): "There is no current through A $\rightarrow$ B and B $\rightarrow$ C. Thus, from $V{=}R \cdot I$ follows $V_{AB}{=}V_{AC}{=}0\,V$. There is current through A $\rightarrow$ D, thus $(I{\neq}0)$ $\Rightarrow V{\neq}0$."[32]

This misconception differs from the other ones in two ways. Firstly, it is the only misconception that is not primarily about voltage or voltage's relation to current, but about Ohm's Law and its application. Secondly, while the other misconceptions were identified in the context of open circuits, they effected voltage in general. The misconception that Ohm's law applies to open circuits, however, is specific to open circuits.

7.4.4.1 *Frequency of Misconceptions*

To analyze the frequency of the different misconceptions, a two-tier exam question (shown in Figure 7.17) was designed that is based on their differences. The question directly asks about the voltage across the open switch (Task 1.4.1). In addition to the correct answer, students have to select one of the five explanations (Task 1.4.2). Students only received credit for the question if their choices for Task 1.4.1 and Task 1.4.2 were both correct. The explanations were phrased to be general, factual statements, whenever possible. It was also made sure that for each answer there would be at least one suitable explanation. Based on the scheme of answers used for other tasks in the exam, four different answering options were used. As the standardized answering form only allowed for five possible answers, only five explanations could be used. Thus, students were presented with two different explanations for the zero voltage answer (A).

The design of two-tier multiple-choice questions is described in Section 5.3.3.

The two explanations that fit the zero volt answer are explanations A and C. Explanation A is the generic statement "without current there can be no voltage", which fits the ideas *voltage is a property of current*, *voltage is caused by current*, or *voltage and current always appear together*. Explanation C is an algebraic description of the *incorrect use of Ohm's Law*. The equation $V = I \cdot R$ was used regularly students' free-response explanations.

32 German original: "Durch A $\rightarrow$ B und B $\rightarrow$ C fließt kein Strom, nach $U{=}R \cdot I$ gilt also $U_{AB}{=}U_{AC}{=}0\,V$. Durch A $\rightarrow$ D fließt Strom $(I{\neq}0) \Rightarrow U{\neq}0$."

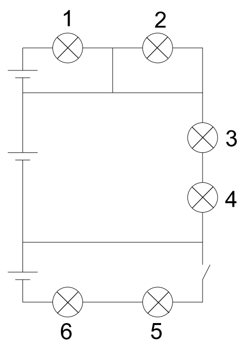
The misconception that *voltage is a substance that moves through the circuit, but cannot pass an open switch* was not included as a explanation, as it seemed to be very rare in the free-response explanations. The three misconceptions associated with explanation A were not further differentiated, as the differences between these misconceptions are somewhat vague and would have required a detailed explanations, which likely would have been very long.

The distribution of students' answers to the exam question is listed in Table 7.16. As the exam was given at the end of the course EE1ME in 2015, the participating students had participated in three Tutorials on DC circuit analysis, including the Tutorial on the electric potential described in Chapter 9. Almost 90% of students selected one of the intended answer–explanation pairs. The three most frequent responses were the correct answer and explanation as well as the common incorrect answer of no voltage across the open switch with either of the proposed misconceptions. The almost even split in answers to the two misconceptions might either mean that students could not differentiate or decide between the two proposed misconceptions or that indeed both proposed misconceptions are about equally frequent. However, as evidence for both these kinds of answers have been observed in interviews and written responses, it seems fair to assume the latter.

Task 1

The three batteries in the circuit at right are identical and can be treated as ideal voltage sources. The long line indicates the positive terminal of a battery. All six bulbs are identical and all occurring voltages are within operating range of the bulbs.

The switch is open.



Task 1.1 (2 points, if both answers are correct)

Task 1.4 (2 points, if both answers are correct)

Task 1.4.1	**The voltage at the switch is**
A	equal to 0 V
B	larger than 0 V but less than one battery voltage
C	equal to one battery voltage
D	larger than one battery voltage

Task 1.4.2	**because**
A	without current there can be no voltage
B	there is no voltage at bulbs 5 and 6
C	$V = R \cdot I$ applies with $I = 0$ A
D	there are three batteries in the circuit
E	a third of the voltage drops at each of the bulbs and the switch, respectively

Figure 7.17: Two-tier exam question on the voltage across an open switch. This question was used in an exam of EE1ME in 2016 (Appendix E.18).

Table 7.16: Distribution of answers and explanations for the question shown in Figure 7.17. N=356. To improve readability, answer combinations given by 10% of students or less are printed in gray font.

	Task 1.4.1				
Task 1.4.2	A	B	C	D	∑
A	21 %	0 %	0 %	0 %	22 %
B	5 %	1 %	31 %	1 %	37 %
C	26 %	1 %	1 %	0 %	28 %
D	0 %	1 %	1 %	3 %	5 %
E	0 %	7 %	1 %	0 %	8 %
∑	52 %	10 %	34 %	4 %	

7.5 ANALYSIS OF KVL VIOLATIONS AND COMPARISON WITH KCL

Section 7.4 showed that many students incorrectly believe the voltage across an open switch to be zero. As for example described on page 146, many student answers concerning the voltage across the open switch were incompatible with KVL. The test presented in this section provides a deeper analysis of this phenomenon and compares the consistency of student answers regarding KVL and KCL.

The test was given to students in the course EE1ME in 2013/14 as part of their exam. The relevant part of the test is shown in Figure 7.18. Questions 1.1 to 1.3, which are not shown in the Figure, asked students to compare the brightness of bulbs A and B, A and C, and A and E. These questions allowed students to familiarize themselves with the circuit. As shown in the figure, students were explicitly told to model the battery as an ideal voltage source, which was consistent with an assumption they had made throughout the Tutorials that were part of the course. During the exam, a clarifying announcement was made that removing bulb D would result in the wire between points Y and Z being disconnected.

The full test is presented in Appendix E.11 (p. 424).

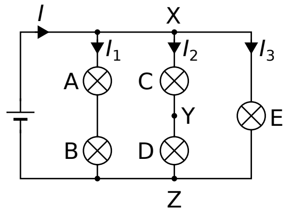
Student answers to the test are shown in Table 7.17. The correct answers are highlighted in green font. Overall, 486 students participated in the exam. 479 of these answered all questions shown in the table. The remaining 7 students are excluded here.[33]

Relevant for the analysis of student answers conflicting with KVL and KCL are not the percentages of the individual answers, but is the distribution of answer combinations. Different combinations of answers are shown in Table 7.18.

Table 7.18a shows students' answers about the voltages V_{XY} and V_{YZ}. These two voltages form a loop with the battery. As the battery

33 Task 1.5 (V_{YZ}) was also used in Section 7.4. In that section, the number of participants is reported as 484, since all students were counted who answered task 1.5.

Problem 1 (8 points)
The battery in the circuit at right can be treated as an ideal voltage source. The long line indicates the positive terminal of the battery. All five bulbs are identical and all occurring voltages are within the operating range of the bulbs.



Task 1.1 (1 point)

Now, bulb D is removed from its socket.

Task 1.4 (1 point)
The absolute value of the voltage between nodes *X* and *Y*, $|U_{XY}|$,…

Task 1.4	**A**	**B**	**C**	**D**	**E**
	increases,	stays the same,	decreases to 0,	decreases, but not to 0.	

Task 1.5 (1 point)
The absolute value of the voltage between nodes Y and Z, $|U_{YZ}|$,…

Task 1.5	**A**	**B**	**C**	**D**	**E**
	increases,	stays the same,	decreases to 0,	decreases, but not to 0.	

Task 1.6 (1 point)
The absolute value of the current of the battery, $|I|$,…

Task 1.6	**A**	**B**	**C**	**D**	**E**
	increases,	stays the same,	decreases to 0,	decreases, but not to 0.	

Task 1.7 (1 point)
The absolute value of the current through bulbs A and B, $|I_1|$,…

Task 1.7	**A**	**B**	**C**	**D**	**E**
	increases,	stays the same,	decreases to 0,	decreases, but not to 0.	

Task 1.8 (1 point)
The absolute value of the current through bulb E, $|I_3|$,…

Task 1.8	**A**	**B**	**C**	**D**	**E**
	increases,	stays the same,	decreases to 0,	decreases, but not to 0.	

Figure 7.18: Question testing students consistency in answers regarding KVL and KCL in the context of an open circuit. This question was used in an exam in EE1ME in 2014 (Appendix E.11). Tasks 1.1 to 1.3 are not shown. The dashed line indicates a page break.

behaves as an ideal voltage source, the voltage across it is constant. This property of the battery voltage limits the combinations of answers about V_{XY} and V_{YZ} that comply with KVL. As the battery voltage stays the same, the voltages V_{XY} and V_{YZ} cannot both increase or both decrease. Based on KVL, it is also impossible that one of the volt-

Table 7.17: Student answers to questions shown in Figure 7.18. Correct answers in green font. $N = 479$.

		Answer			
		a	b	c	d
Task	Quantity	increases	stays the same	decreases to 0	decreases, but not to 0
1.4	$\|V_{XY}\|$	21 %	18 %	51 %	11 %
1.5	$\|V_{YZ}\|$	12 %	16 %	62 %	10 %
1.6	$\|I\|$	29 %	41 %	1 %	30 %
1.7	$\|I_1\|$	49 %	42 %	1 %	11 %
1.8	$\|I_3\|$	53 %	33 %	2 %	11 %

ages stays the same while the other one increases or decreases. Such answering combinations that conflict with KVL are marked in red in Table 7.18a. Overall, 70% of students selected an answer combination conflicting with KVL.

Tables 7.18b, 7.18c, and 7.18d show the answer combinations for students' answers about the currents I, I_1, I_3. For each of the three answers on the change of I, a separate table shows the distribution of answer combinations for the currents I_1 and I_3.

Assuming no current flows through the branch with the removed bulb, and if the current I stays the same (Table 7.18b), at least one of the currents I_1 or I_3 must increase. The same is true if the current I increases (Table 7.18c). Every other answer combination conflicts with KCL and is marked in red in the tables. On average, 27% of students selected an answer combination conflicting KCL.

If the current I decreases, but not to zero, every answer combination for currents I_1 and I_3 could technically be compliant with KCL, depending on the their values before the bulb was removed. The currents could be determined relative to each other, based on the fact that all bulbs are equal. However, such an argument becomes moot considering that none of the currents can increase by removing a bulb in a parallel branch. If the current I decreases to zero and no current flows through the branch wit the removed bulb, the currents I_1 and I_3 must both decrease to 0. Only 6 students stated that the current I would decrease to zero. None of these stated that I_1 or I_3 would also decrease to zero. The distribution of answers to these two cases is summarized in Table 7.18d. When including the 6 students who stated the current I would become zero but I_1 and I_3 would not, the average of answer combinations conflicting with KCL increases to 28%.

70% of students' answers conflicted with KVL. Most students either did not understand KVL or did not consider the battery to behave like an ideal voltage source, even though it was stated to behave as such.

In contrast, of those students that incorrectly treated the battery as a current source (Table 7.18b), about 80% gave answers that are consistent with KCL. From the fact that so many students with a common misconception did not give answers that contradicted KCL, it can be concluded that the application of a conservation law was not problematic for students. Instead, the recognition that such laws hold for the specific quantities of voltage and/or potential proved to be difficult. If students had understood "the physics", they would have been able to do "the math".

Table 7.18: Answer combinations for the questions shown in Figure 7.18 for voltages (a) and currents (b-d). Correct answer combinations are indicated by green, underlined font. While table (a) includes all students who participated in the test, tables (b) to (d) are split depending on students' answers to Task 1.6. The answer combinations marked in red violate KVL or KCL, recognizing that the voltage across the battery stays the same and there is no current through the branch with the removed bulb.

(a) All students. N = 479.

	Task 5 (V_{YZ})			
Task 4 (V_{XY})	a	b	c	d
a	2 %	2 %	14 %	2 %
b	2 %	5 %	7 %	3 %
c	<u>8 %</u>	7 %	34 %	2 %
d	0 %	1 %	8 %	2 %

Combinations conflicting KVL: 70%

(b) I stays the same. N = 195.

	Task 8 (I_3)			
Task 7 (I_1)	a	b	c	d
a	59 %	2 %	2 %	2 %
b	12 %	12 %	1 %	2 %
c	0 %	0 %	1 %	0 %
d	2 %	1 %	1 %	4 %

Combinations conflicting KCL: 21%

(c) I increases. N = 136.

	Task 8 (I_3)			
Task 7 (I_1)	a	b	c	d
a	41 %	4 %	1 %	4 %
b	8 %	26 %	1 %	2 %
c	1 %	0 %	0 %	0 %
d	4 %	1 %	0 %	7 %

Combinations conflicting KCL: 37%

(d) I decreases or becomes 0. N = 148.

	Task 8 (I_3)			
Task 7 (I_1)	a	b	c	d
a	16 %	1 %	0 %	0 %
b	7 %	<u>57 %</u>	1 %	3 %
c	0 %	0 %	0 %	1 %
d	3 %	0 %	1 %	10 %

7.6 SHORT CIRCUITS[34]

The research on students' understanding of short circuits seems to be even more scarce than that on open circuits discussed in Section 7.4. It can be separated into two phases: *early investigations*, which were mostly conducted in the first half of the 1980s, and *recent studies*, starting at the end of the 1990s, that build upon the earlier results and present more comprehensive tests. The research of both periods was conducted with high school and university students, the vast majority not being engineers. After an overview of the research from both periods, newly gathered data on engineering students is presented.

Section 3.1 describes different periods of prior research.

7.6.1 *Early Investigations*

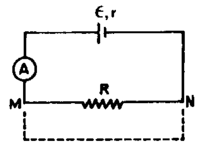
First investigations into students' understanding of short circuits were both qualitative and quantitative. Fredette and Clement (1981) for example reported on interviews in which students were given a resistor and capacitor connected in parallel. This parallel connection was then connected to a battery – with both terminals of the battery connected to the same "end" of the parallel connection. Johsua (1984) reported on a study that used different circuit diagrams containing short circuits in different arrangements. Each circuit consisted of a resistor connected to a battery. To one of the connecting wires, additional components were connected, like a second (parallel) wire, a wire loop, or a resistor that effectively was short-circuited. The authors of both studies reported that students had difficulty correctly interpreting the short circuits and even completely ignored short circuits in some cases.

A multiple-choice question (see Figure 7.19) on short circuits was presented by Cohen et al. (1983) as part of a test to investigate students' understanding of simple electric circuits. The answering options related to multiple concepts. Answering option *a* directly addresses the incorrect belief that short circuits have no effect on the current through or voltage across the short-circuited elements. Answering option *d* is correct.

Table 7.19 shows the distribution of answers to the question as reported by Cohen et al. (1983). Further data from Picciarelli et al. (1991b), who used the test same test, are also listed. Cohen et al. (1983) did not report on any blank answers, while Picciarelli et al. (1991b) had a considerable number of students who did not commit to an answer. Besides this difference, however, there is not a large variation between the different cohorts. Most subjects choose one of the two

34 The two tasks discussed at the end of this section (see Figures 7.23 and 7.27) were developed by Frederik Thale as part of his bachelor's thesis. The author of this research project, however, had strong influence on their design. Except for the design of the two tasks, the research presented in this section was conducted independently by the author of this thesis.

9. A resistor is connected, through an ammeter, to a battery which has an e.m.f. ϵ and internal resistance r (see figure). Now the points M and N are connected using a short, thick piece of copper wire. Consequently:



a The current flowing through R does not change significantly.
b The current flowing through the wire is very small, because the p.d. across it is very small.
c The current flowing through the ammeter does not change, but the current in the circuit flows mainly through the copper wire.
d The current flowing through the ammeter increases, and most of the current in the circuit flows through the copper wire.

Figure 7.19: Question 9 from the test developed by Cohen et al. (1983). Reproduced with the permission of the American Association of Physics Teachers.

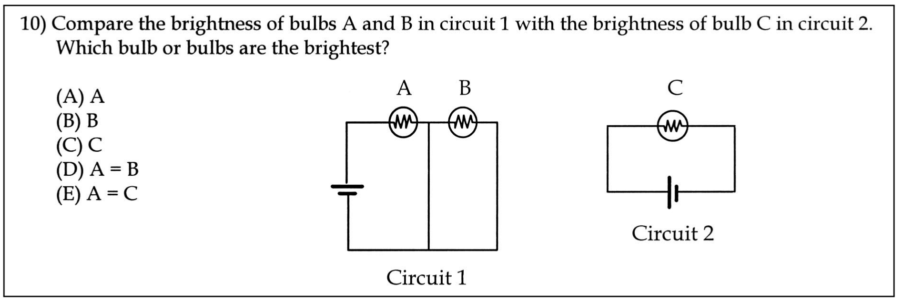
Table 7.19: Student answers to the question shown in Figure 7.19.

		Answer			
Study & Cohort	N	a	b	c	d
Cohen et al. (1983)					
Students	145	9 %	4 %	32 %	55 %
Teachers	21	5 %	5 %	28 %	62 %
Picciarelli et al. (1991b)					
Sample 1, pre-test	173	11 %	1 %	37 %	26 %
Sample 1, post-test	74	9 %	3 %	35 %	28 %
Sample 2	63	9 %	7 %	28 %	44 %

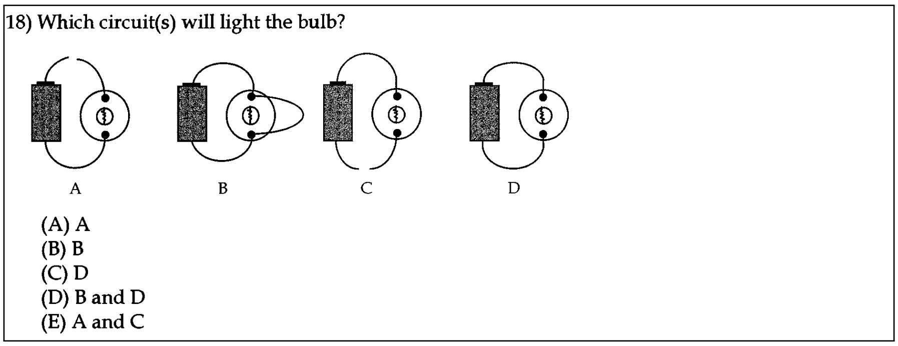
answers (c and d) that correctly state that most of the current flows through the inserted copper wire. Only 9% to 11% of students selected option *a* that states the current through the resistor would not change. These students ignored the short circuit.

7.6.1.1 *Students' Reasonings*

Based on publications by Fredette and Clement (1981), as well as van Aalst (1985) and Johsua (1984), seven different arguments why students might fail to recognize a short circuit were compiled by Engelhardt (1997). Several of these are based on visual perception, i. e. how students take in and interpret the information presented in a circuit diagram. Others, however, represent reasoning that would fit a misconception: Fredette and Clement (1981) for example report on a student who believes that wires "don't really do anything" (p. 283). Wires do not have any resistance and likely are "only minor participants in many of the problems [students] had encountered" (Engel-



(a) Question 10



(b) Question 18

Figure 7.20: Two questions from version 1.0 of the DIRECT by Engelhardt (1997). Reproduced with permission.

hardt, 1997, p. 36). For each different circuit element, students usually learn "what that element does". Wires are treated as ideal connections between circuit elements, but not as the "short-circuit circuit element". This argument might explain why students might ignore a wire. Johsua (1984) and van Aalst (1985) argue differently. They observed students who used *functional reasoning*: A circuit element placed in a circuit must have a purpose. Consequently, there must be current flowing through or voltage dropping across it, even when the element is short-circuited.

7.6.2 *Recent Studies*

Based on these findings more comprehensive tests have been developed. Key results from the test by Engelhardt (1997) and Peşman and Eryılmaz (2010) are presented in the following.

The DIRECT by Engelhardt (1997) contains several questions that involve short circuits. Two of these ask students about the brightness of a short-circuited bulb in comparison to a bulb that is not short-circuited.

Question 10 (see Figure 7.20a) asks students to compare the brightness of three bulbs based on circuit diagrams. Here, students must recognize that bulb B is short-circuited in order to correctly answer that both bulbs A *and* C are brightest. Subsequently, question 18 (see

Table 7.20: Student answers to two questions from the DIRECT test for different cohorts and versions of the test (see Figure 7.20 for version 1.0).

(a) Question 10

			Answer				
Version	Cohort	N	A	B	C	D	E
1.0	High School	454	2 %	1 %	55 %	12 %	30 %
	University	681	3 %	1 %	52 %	10 %	34 %
1.1	High School	251	3 %	0 %	63 %	5 %	29 %
	University	441	3 %	1 %	50 %	9 %	37 %

(b) Question 18

			Answer				
Version	Cohort	N	A	B	C	D	E
1.0	High School	454	1 %	4 %	24 %	70 %	1 %
	University	681	0 %	1 %	31 %	67 %	0 %
1.1	High School	251	0 %	2 %	46 %	50 %	1 %
	University	441	0 %	2 %	46 %	51 %	0 %

Figure 7.20b) presents students with four circuits that are represented not as circuit diagrams but as simplified drawings of the circuit components and their connections. Students must identify that only the bulb in circuit D glows, as circuits A and C are not closed and the bulb in circuit B is short-circuited.

While Question 10 did not change from version 1.0 to 1.1 of the test, Question 18 did. According to Engelhardt (1997), "interviews revealed that students did not understand the light bulb in a socket symbol in question 18 so [for version 1.1 of the test] the circuits were re-drawn without the socket" (p. 84). The revised question, which is not shown here, depicts the battery and bulb from the side. In the author's opinion, the short circuit is more difficult to identify in version 1.1 of the test. Engelhardt (1997), however, reports that the fraction of correct answers increased. This seems to imply that students previously answered incorrectly because they did not understand the circuit symbols shown in Figure 7.20b.

Table 7.20 shows the distribution of students' answers Engelhardt (1997) reported for both questions. With Question 10, between 50% and 63% of the students in each cohort stated that bulb C would glow brightest, i. e. missed the short circuit across bulb B or believed it had no effect. The correct answer was chosen by 29% to 37% of students,

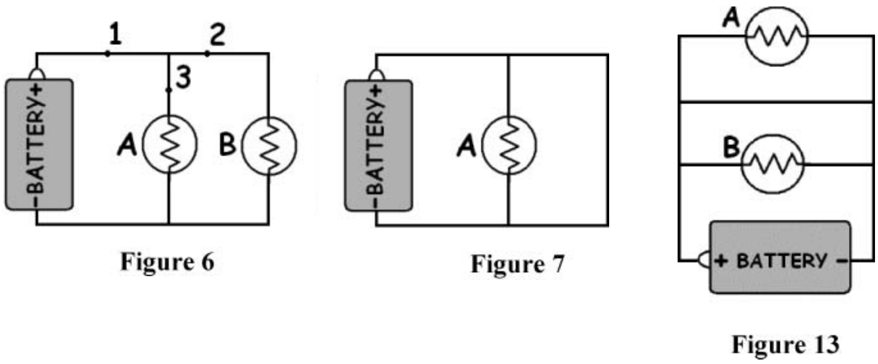


Figure 7.21: Different circuits from short circuit questions in the test developed by Peşman and Eryılmaz (2010). Reproduced with permission.

with the other three answering options being selected by no more than 15% of students. Question 18 shows similar results with 50% to 70% of students believing the bulbs in circuits B and D to light, i. e. missing the short circuit across the bulb in circuit B or believing it has no effect. Almost all students who did not select this answer, selected the correct one. The difference between versions 1.0 and 1.1 of the test, however, is stark. The frequency of the dominant answer dropped from 67%–70% to 50%–51%. Based on this lower frequency, the answer that the short circuit has no effect occurs about equally often in students' answers to Questions 18 and 10.

Peşman and Eryılmaz (2010) reported on the development of a test that measures the frequency of 11 common misconceptions about simple electric circuits using 12 three-tiered questions. The test was administered to 124 grade 9 high school students from Turkey, aged 14 to 16. One of the misconceptions covered by their test was "the short circuit misconception, in which wires with no electrical devices are ignored when analyzing an electrical circuit". This misconception is linked to answers to three different questions. These were for example to compare the brightness of the bulb labeled A in the circuits "Figure 6" and "Figure 7" in Figure 7.21 or to compare the brightness of bulbs A and B in the circuit "Figure 13" in Figure 7.21. Peşman and Eryılmaz (2010) found that 57% of their students gave answers that indicated the short circuit misconception, when only the first tier of each answer was considered. When also students' explanations (tier two) were considered, this number sank to 30% and when students who were unsure of their answer (tier three) were excluded, only 20% of students held the misconception.

See Section 5.3.3 (p. 67) for a description of two- and three-tiered questions.

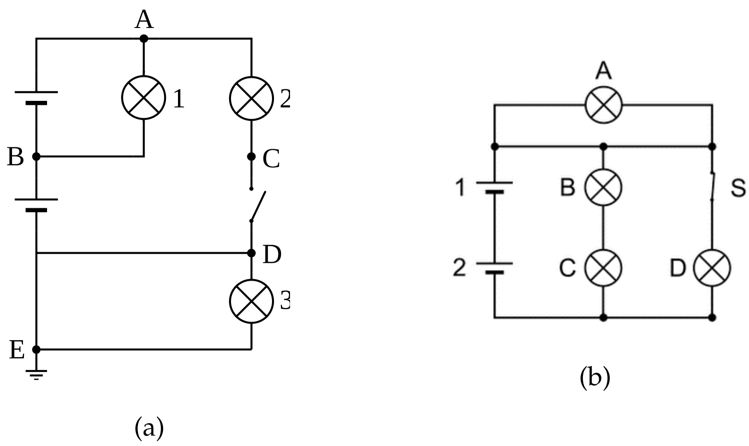


Figure 7.22: Circuits used in initial tests about short circuits.

7.6.3 *Data Gathered as Part of this Study*

For full test, see Appendix E.13 (p. 432). The development of the question is described in Section 9.6.4 (p. 247).

Since short circuits are usually treated as a trivial case in engineering education and not extensively discussed in education research, the research presented in this thesis initially did not contain any questions on that subject. A post-test developed in 2015, however, contained a short-circuited bulb (see Figure 7.22a). This bulb was only added to increase the complexity of the circuit. The last question of the test asked students if the brightness of the bulbs changed when the switch was closed. As bulb 3 is always short-circuited, it never glows, i. e. its brightness does not change. Surprisingly, 42 of 97 students indicated that bulb 3 would glow brighter when the switch was closed. These results indicate that a significant fraction of students did not recognize the short circuit.

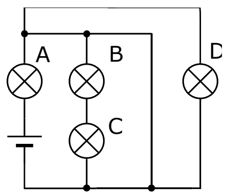
The full test is presented in Appendix E.14 (p. 436).

To verify these results, a similar question was included in an exam in EE1ME. While the previous question had asked about a change in the brightness of the short-circuited bulb, the new question addressed a static situation. Given the circuit shown in Figure 7.22b, students were asked if bulb A is a) *off (i. e. does not glow)*, b) *dimmer than bulb* D*, but not off*, c) *equally bright as bulb* D, or d) *brighter than bulb* D. Since all questions in that task of the exam were two-tier multiple-choice questions, this question also contained five reasons for students to select from. These explanations covered three relevant arguments why the bulb might be glowing: a) the bulbs sharing/dividing[35] the voltage, b) bulb A being in a closed circuit, and c) the arrangement of the bulbs. Two other explanation d) and e) could be used to argue why the bulb might not glow. About half of the students (47%) selected answer b), c), or d), i. e. believed bulb A to glow. The vast majority of students selected one of the three explanations described above,

35 The test was in German and used the word “teilen”, which can mean both. See p. 191.

Task 3

The circuit at right contains identical bulbs and a battery which can be treated as an ideal voltage source.



a) Rank bulbs A, B, C, and D according to their brightness. State explicitly, if two bulbs have the same brightness or one bulb does not glow at all. Use the relational operators >, <, and =.

Briefly explain your reasoning.

Figure 7.23: Question to test different configurations of short circuits.

with explanations a) and c) each being selected about twice as often as explanation b).

These two tests clearly showed that even after instruction, a sizable fraction of students in the course EE1ME had difficulties with short circuits. To further investigate students' understanding of short circuits, two new questions were developed.

7.6.3.1 *Different Configurations of Short Circuits*

The task shown in Figure 7.23 was designed to test if students recognize short circuits more frequently when they are closer to the element being short-circuited. It was administered five times overall in different courses. In some cases, the task contained an introductory question, where students for example were asked to describe the connection of the bulbs. The main part of the question, ranking the four bulbs by their brightness, however, was identical in all cases.

The full tests are shown in Appendices E.21 (p. 466), E.15 (p. 440), E.16 (p. 444), E.20 (p. 462), and E.23 (p. 470).

Table 7.21 gives an overview of students' answers about bulbs B, C, and D. Students were considered to have identified a short circuit when they either ranked a bulb to not glow or indicated the bulb to be either off or short-circuited in their explanation. In all five cohorts, the majority of students (at least 87%) identified either all three or none of the bulbs as short-circuited. Only small fraction of students (9% to 12% in sum per test) identified only the short-circuits across bulbs B and C or across bulb D. In most cohorts, twice as many students only identified the short circuits across B and C compared to those that only identified that across D. A negligible number of students gave a different answer, e. g. by only recognizing bulb B as short-circuited.

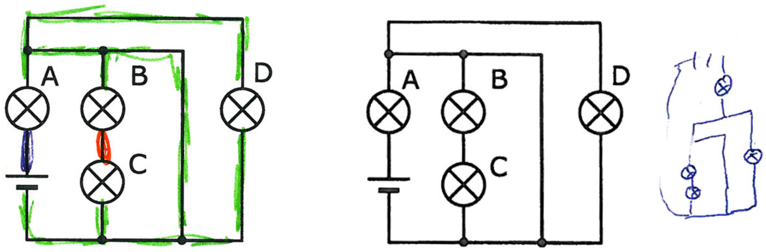
Table 7.21: Percentages of students in different tests who were able to identify short-circuited bulbs in the circuit shown in Figure 7.23. N* is the number students who participated in the test. All percentages are in respect to N, the number of students who believed bulb A to glow and also used bulbs B, C, and D in their ranking.

				Short circuit identified			
Cohort	Week	N*	N	all	only B & C	only D	none
EE1UK, pre	1	124	98	23 %	8 %	4 %	64 %
EE1ME, 2015	4	275	241	19 %	7 %	4 %	70 %
EE1EE, 2015	6	200	187	43 %	7 %	2 %	48 %
EE1ME, 2016	7	181	176	57 %	7 %	4 %	32 %
EE1UK, post	7	79	72	65 %	11 %	1 %	22 %

While at least 87% of students in each test were able to correctly identify either all or none of the short circuits, the ratio between these two groups differs greatly between the different cohorts. In some courses, only about ⅕ of students was able to identify all short circuits, but in one course almost ⅔ were able to do so. This difference can be explained by the week the cohort was tested. Cohorts that had more instruction, i. e. where the test was given later in the semester, performed better. It is, however, unclear if this difference is simply caused by students becoming more adept in reading circuit diagrams or the effect of one or more Tutorials. Students in the cohort EE1UK (pre) had no university instruction in electrical engineering. Students in the cohort EE1ME (2015) had four weeks of traditional lectures and participated in two Tutorials (*Current and Resistance* and *Voltage*). Students in the cohort EE1EE had 6 weeks of traditional instruction but had not participated in any Tutorial. The students in the cohorts EE1ME (2016) and EE1UK (post) had six weeks of instruction, including three Tutorials (*Current and Resistance*, *Voltage*, and *Electric Potential*).

An overview of the semester structure of the different courses is presented in Appendix A (p. 305).

It could be argued that students become better at identifying short circuits simply by attending courses and therein practicing to read circuit diagrams, as the students in the cohort EE1EE performed moderately well in the course without the use of any Tutorials. Alternatively, it could be argued that the students in the course EE1EE are simply better than students in the other courses, due to the fact that they major in electrical engineering and not some other branch of engineering. The difference between the first two and the last two cohorts in Table 7.21 can then be explained by the last two cohorts having participated in the Tutorial about the electric potential. Chapter 9 discusses that Tutorial and why it would help students to better



(a) A = B = C > D = 0 (b) A > D > B = C = 0

Figure 7.24: Students' markings in the circuit diagrams of the question shown in Figure 7.23 (1 of 3). The respective ranking of the bulbs by brightness is shown below the image.

understand voltage. The arguments made there could also be applied to short circuits.

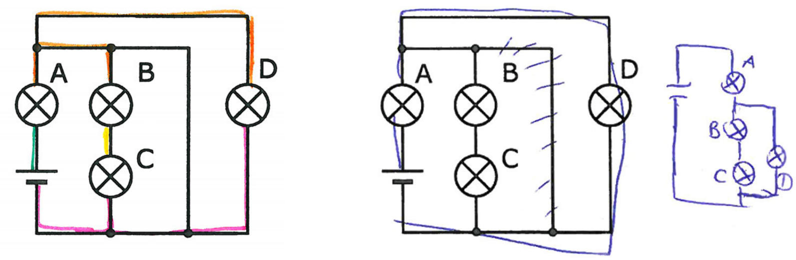
7.6.3.2 *Student Reasonings*

In this subsection, student's reasonings will be discussed. Some of these reasonings are based on color-coded circuits. Color-coding had been introduced a few weeks prior to the test in 2016 as part of a Tutorial (see Section 9.6 on the development of that Tutorial). In that Tutorial, students were instructed to "mark all points that are not separated [...] by a circuit element with the same color". They then discovered that regions of the same color have the same potential. One task in that Tutorial addressed the fact that bulbs which have the same color on both of their terminals do not glow as there is no voltage drop across them.

As described above, a small fraction of students could identify either only bulbs B and C or only bulb D as short-circuited. Only identifying the short circuit across B and C likely is caused by the short circuit being closer to bulbs B and C. One student for example drew the equivalent circuit shown in Figure 7.24b. This circuit has the battery moved to the top, separating it from the load. The equivalent circuit also shows that bulb A is connected in series to the rest of the circuit. The short circuit, however, is still connected to the branch of B and C, as can be seen by the short circuit wire not going directly up but instead making a connection above B and C. The student ranked the bulbs as $A > D > B = C = 0$ and explained that "D is in series with A"[36]. Clearly, the student did not recognize that the short circuit is not only in parallel to bulbs B and C, but also to bulb D.

Less students only identified bulb D as short-circuited. Due to the small sample size, not much is known about these student's reasonings. The color coding applied to the circuit shown in Figure 7.24a, however, indicates a possible reason for such an answer. The student

36 German original: "D is in Reihe zu A"



(a) A > D > B = C

(b) A = B = C = D

Figure 7.25: Students' markings in the circuit diagrams of the question shown in Figure 7.23 (2 of 3). The respective ranking of the bulbs by brightness is shown below the image.

identified bulb D as short-circuited. This is consistent with bulb D having the same color, i. e. potential, on both of its terminals. Bulbs B and C, in contrast, were not identified as short-circuited. These two bulbs do not have the same color on both sides. Following the rules given for color-coding, the student used a different color for the wire between B and C than "outside" of B and C. The student would then have to determine that the red wire (between B and C) has the same potential as the green wire ("outside" of B and C). However, to do so, the student would need to see that no voltage drops across B and C, i. e. recognize the short circuit. Alternatively, students would need to recognize that B and C can be treated as a unit before analyzing the two individual bulbs.

In this analysis, students who indicate a bulb to be off are assumed to believe it to be short-circuited. Therefore, it might be tempting to assume that students who did not indicate a bulb to be off, simply forgot to note that the bulb's brightness was zero. If that were the case, more students would have been able to identify short circuits, than was indicated in Table 7.21. However, the written explanations contain many examples of students being very clear about their answer. The student's answer shown in Figure 7.25b for example shows the branch with the short circuit crossed out. The student has drawn a "simplified" circuit diagram next to the one given in the task. This "simplified" diagram has the short circuit removed.

Figure 7.25a shows the circuit diagram of a student who used color-coding. This student did not color the short-circuit itself and used different colors for the wires at top (orange) and at bottom (pink). The student's ranking (A > D > B = C) were correct if the short circuit did not exist and their explanation also does not mention the short circuit: "B and C are connected in series and share the same current, thus they both glow dimmer. B and C are in parallel to D,

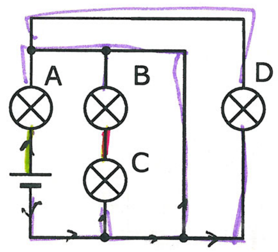


Figure 7.26: Student's markings in the circuit diagram of the question shown in Figure 7.23 (3 of 3). The student correctly ranked the bulbs by brightness as: $A > B = C = D = 0$.

thus D glows as bright as B and C combined."[37] It seems as if this student believed the short had no effect on the rest of the circuit and consequently used color coding as if this short circuit did not exist.

While there is usually not much information to be gained from discussing students' explanations for correct answers, one particular example seems noteworthy: A student seemed to have only recognized the short circuit with the help of color-coding. They noted: "Very strange. After drawing the potentials onto the conductors it seems that all bulbs except A are bypassed."[38] The student's color-coded circuit is shown in Figure 7.26.

7.6.3.3 *Direct Confrontation and Misconceptions*

With the task discussed above, it could be argued that some students did not identify bulbs as short-circuited because they did not notice the shorts. Explanations also often were vague as students had to describe their thinking about four bulbs at once. The task shown in Figure 7.27 was designed so that students were directly confronted with a short circuit, while not naming it as such. Part a) asked students to rank all bulbs by brightness. This ranking allowed students to familiarize themselves with the circuit before the change was introduced. The ranking also allowed to verify that students correctly understood the circuit. In part b), a wire was added that functioned as a short circuit. Students were asked to give a separate explanation for the change of brightness for each of the three bulbs. Consequently, students' answers were more explicit than with the previous question. The test was administered in the 7th week of the course EE1ME in 2015. Three weeks earlier the same cohort had also participated in the test described before. Of 200 participants, 181 correctly ranked the brightness of the bulbs in part a) as $A > B = C$. Of these, 59% correctly stated that bulbs B and C would turn off when the short circuit was added.

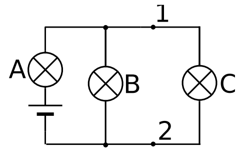
The full test is presented in Appendix E.17 (p. 448).

37 German original: "B und C sind in Reihe geschaltet und teilen sich den Strom, damit leuchten beide schwächer. B und C sind zu D parallel geschaltet und damit leuchtet D gleich wie B und C zusammen."

38 German original: "Sehr komisch. Nach dem Einzeichnen der Potentiale in die Leiter scheint es so als würden alle Lampen bis auf A überbrückt werden."

Task 1

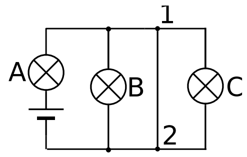
The circuit at the right contains an ideal battery and 3 identical bulbs.



a) Rank the bulbs A, B, and C by their brightness. Use the relational operators >, <, and =. State explicitly, if two bulbs are equally bright or a bulb does not glow at all.

Explain your reasoning.

b) Points 1 and 2 are now connected with an ideal conductor. Does the brightness of the individual bulbs change in comparison to before? State your answer for each of the bulbs A, B, and C. Please also explain your reasoning.



Compared to before the insertion of the ideal conductor, bulb A now is: ☐ brighter ☐ equally bright ☐ darker, but still glowing ☐ darker and does not glow anymore	Explanation:
Compared to before the insertion of the ideal conductor, bulb B now is: ☐ brighter ☐ equally bright ☐ darker, but still glowing ☐ darker and does not glow anymore	Explanation:
Compared to before the insertion of the ideal conductor, bulb C now is: ☐ brighter ☐ equally bright ☐ darker, but still glowing ☐ darker and does not glow anymore	Explanation:

Figure 7.27: Question that directly confronts students with a short circuit.

Conversely, 16% stated that both these bulbs would still glow, i. e. ignored the short circuit. Another 14% stated that bulb C would not glow anymore, but bulb B would glow brighter. An additional 10% of students stated that bulb C would not glow anymore, but that bulb B would become dimmer or not change. Overall, 41% of students indicated that at least one of the bulbs would still glow. This number is consistent with the previous test (Table 7.21) where 43% of students in the 7th week of EE1ME in 2016 missed at least one short circuit.

Introducing the short circuit in the middle of the task results in explanations that revealed misconceptions more clearly:

Misconception: *Tendency to reason sequentially and locally, rather than holistically (2 of 2)*

As McDermott and Shaffer (1992) and Engelhardt (1997) report, students often employ *local* or *sequential reasoning*. They do not consider that every element can affect the distribution of current and voltage in all parts of the circuit. When one circuit element is changed, the change often is thought to only affect elements "downstream", not ones closer to the source. This reasoning can also be found in answers regarding the short circuit. A student for example explained "Bulb C is sort of 'cut off' as the current flows through the ideal conductor."[39] For bulb B, the student first answered the bulb would become *brighter*, but then changed their answer to *darker, but still glowing*, explaining "The current that previously went through B and C now mainly goes through the ideal conductor, but partially still through B."

While there are also clear-cut examples of students employing strict local reasoning (6 of 181) where bulbs A and B are unchanged and bulb C turns off, more common were answers that mixed local reasoning with other ideas. The student quoted above for example employed local reasoning but also incorporated the idea that "current takes the path of least resistance" as students commonly argue.

Misconception: *Current splits evenly at each node*

A special form of local reasoning is the misconception that current which flows into a node splits evenly to each wire "leaving" the node. For students who have this misconception, adding a short circuit simply means adding another wire for current to be split to. One student for example argued that "The current splits once at the node to B, and a second time at the node to 1, consequently, even less current flows through C and it becomes dimmer."[40] As with local reasoning, the clear examples (bulbs A and B are unchanged and bulb C becomes dimmer) are not particularly common (8 of 181). While the author is not aware of any reports on this misconception in literature, it seems likely it also occurs with other populations.

Misconception: *Short circuits have no effect*

As described on page 159, Fredette and Clement (1981) observed a student who believed short circuits have no effect, they "don't really do anything" (p. 283). Besides the drawings shown in Figure 7.25, some answers to this question also suggest the same belief. One student for example argued that "Ideal conductors have no resistance. Thus, there is no change as they [the bulbs] were already in parallel before."[41] Another student argued that "As the conductor is ideal, there is no resistance between [points] 1 and 2."[42] The student seems to argue that no resistance means no effect. This student seemed to believe that a resistance is required to cause an effect.

7.7 CONCLUSION

This chapter contained several investigations on students' understanding of current and voltage, especially on their understanding of KCL and KVL. The results of these investigations present answers to research questions RQ 1A, RQ 1B, and RQ 2A. In this section, the most im-

39 German original: "Lampe C ist sozusagen 'abgeschnitten', da der Strom über den idealen Leiter läuft."

40 German original: "Der Strom teilt sich sowohl im Knotenpunkt zu B wie im Knotenpunkt zu 1, wodurch noch weniger Strom durch C fließt und somit die Helligkeit nachlässt."

41 German original: "Ideale Leiter haben keinen Widerstand somit macht es keinen Unterschied, da sie zuvor schon parallel waren."

42 German original: "Da der Leiter ideal ist, ist da kein Widerstand zwischen 1 und 2."

portant findings related to each of the three questions are presented. The research questions are repeated in the page margins.

7.7.1 *Findings Regarding* RQ 1A

RQ 1A: *Are the conceptual difficulties with current and voltage identified in physics courses also prevalent in engineering courses?*

Most of the difficulties with current and voltage that had been identified with students in physics courses could also be observed among engineering students. Based on not only the five bulbs test (see Section 7.1), but also the investigations of open and short circuits (see Sections 7.4 and 7.6), the engineering students tested in this study seem to have in general the same misconceptions regarding current and voltage as students in other study programs.

Some of these misconceptions, however, present in a different form. McDermott and Shaffer (1992) for example reported that the students they investigated believed and stated that current was "used up". When answering tests, the engineering students investigated in this study almost never explained their answer by stating that current was "used up". Still, the answers of many students indicated that they actually believed it to be "used up". Instead of "used up", the engineering students use phrases like "the current [...] was eaten" or opined that the second bulb in a series connection "has less juice" (p. 113). This observation might be an example of a synthetic mental model (see Section 2.3.2.1), where a disconnect occurred between students' true beliefs (current is "used up") and the models they have learned to apply in class (current is not "used up"). Like the students investigated by McDermott and Shaffer, the engineering students believed that current was "used up", but were taught to not use that phrase. The underlying misconception, however, was not addressed.

Synthetic mental models were introduced in Section 2.3.2.1 (p. 17) and illustrated with examples in Section 2.3.3.1 (p. 22).

The use of bulbs and batteries in the tests used in this thesis might seem unusual or even problematic for some readers, since these circuit elements are rarely used by electrical engineers. However, these elements were used deliberately, as they helped to prevent students from simply applying algorithms that they had learned and instead required them to use their conceptual understanding. In Section 7.1.5, it was found that the use of these circuit elements has no negative effect on student answers. There was no significant difference in the percentage of correct and incorrect answers for two groups that only differed in the symbol for the source that was used in their test.

The frequency of student difficulties and misconceptions differs, depending on the concept. As reported in Section 7.1, the engineering students overall performed better in the five-bulbs test than the students investigated by McDermott and Shaffer (1992), even when comparing pre-instruction levels of engineering students with students in physics courses, who had completed traditional instruction. Thus, while the engineering students in general showed the same misconceptions, some of these misconceptions occurred less frequently that in other courses.

However, other false beliefs, like that there is no voltage across an open switch, occurred more often among the engineering students tested in this study than among the general population of university students reported upon in Section 7.4.

7.7.2 *Findings Regarding* RQ 1B

RQ 1B: *Are there conceptual difficulties with current and voltage in the electrical engineering curriculum that have not been identified before?*

Some of the misconceptions identified in this thesis had previously not been reported or not been documented in detail.

Questions on students' understanding of open switches had been part of several investigations. These individual tests, however, had previously not been compared. The analysis presented in Section 7.4 shows that the open circuit voltage is a difficult concept for students in all of the cohorts tested. Of more than 5500 students, about half believed there to be zero volt across an open switch. This false belief was prevalent in all cohorts. In 17 of the 20 cohorts investigated, more than 40% of students believed the voltage across the open circuit to be zero. In the course EE1ME, data was gathered over several years. During that time three instructors (A, B, and C) taught the course. Students' answers in these different years stayed mostly the same, indicating that this false belief is not strongly affected by traditional instruction. Several misconceptions regarding the voltage across an open switch were observed, including the incorrect application of Ohm's Law.

McDermott and Shaffer (1992) had found that students failed to recognize that a battery maintains a constant voltage. As reported in Section 7.1, this difficulty was not caused by the use of the battery symbol for the source, but likely by a fundamental misconception about sources. Even in circuits where an ideal voltage source was used, students failed to recognize that the ideal voltage source maintains a constant voltage between its terminals. Of the concepts tested in the five-bulbs test this difficulty presented as the most common problem. With circuit elements closer to the source, however, students more often recognized the constant voltage supplied by the source, indicating that localized reasoning affects this misconception. Many difficulties with voltage sources seem to be caused by current-based reasoning. As shown in e. g. Section 7.2.2, a large number of students preferred current-based reasoning, even in situations where its application constituted an error.

An analysis of interviews on sources (Section 7.3) revealed that students believed the source voltages of voltage sources in parallel and the source currents of current sources in series would add up. This false belief might be caused by the misconception that sources *increase* the current through or voltage across them instead of *defining* the current through or voltage across them.

7.7.3 *Interpretation of Students' Difficulties with Voltage*

Student answers reported in this chapter indicated that students often have more trouble with concepts related to voltage than with those related to current. Von Rhöneck (2008) posits that "Usually students do not develop an independent voltage concept, but interrelate it to the concept of electric current."

A different explanation can be based on Chi's theory of orthogonal categories, introduced in Section 2.3.2.3. Chi (2013) distinguishes between *sequential* and *emergent* processes. She posits that many student difficulties are the result of students not having formed the category of an emergent process, causing them to incorrectly assign concepts to the category of sequential processes. Current is such a sequential process. The agents (electrons) move through a circuit in an ordered manner resulting in a current. While this current splits and recombines, it flows in general in the same direction.[43] The distribution of electric fields in a circuit and thus voltage in a circuit is an emergent process. It has no acting agent. As many students have formed the category of the sequential process, but not the category of the emergent process, they are able to correctly understand current, but not voltage.

As Chi (2013) notes, simply telling students that the distribution of voltage is an emergent process would not help, as in general "students are ignorant of ideas about emergence". Students would first have to become familiar with the category of emergent processes. Chi (2013) claims that "once students have successfully built such an alternative schema with its distinct set of properties [...], they can begin to assimilate new instruction [...] into the category." Thus, after students have become familiar with emergent processes and their properties, they could then use this knowledge to understand how voltage behaves in a circuit.

7.7.4 *Findings Regarding* RQ 2A

RQ 2A: *To what extent is the frequency of the conceptual difficulties reduced when existing Tutorial worksheets are used?*

Many of the common misconceptions regarding current and voltage can be tested with the five-bulbs test and are addressed in the Tutorials *Current and Resistance* and *Voltage*. Sections 7.1 and 7.6 present test results from students who had and had not worked with Tutorials in their instruction. In some cases, there seems to be no learning with only traditional instruction. Several traditionally taught courses performed similarly in the five-bulbs test, even tough some had completed one year of instruction, while other had not. Tutorials greatly helped to reduce those student difficulties that are tested with the

43 At least for the average movement of the electrons. Informal observations by the author suggest that students generally ignore or forget the random movement of electrons.

five-bulbs test. However, some difficulties remained after Tutorial instruction.

The failure to recognize that an ideal voltage source maintains a constant voltage between its terminals was equally common for students who had participated in Tutorials as those who had not, indicating that the problem is not addressed adequately in the Tutorials used.

The fraction of students who failed to recognize a short circuit was lower for students who had participated in Tutorials. Short circuits, however, were not addressed explicitly in the Tutorials. While the Tutorials might still help students to learn to correctly identify short circuits, the data could also indicate that the frequency of difficulties is reduced to a large extent through practice reading circuit diagrams, which is part of traditional instruction.

8 CONTENT-FOCUSED ANALYSIS OF TUTORIALS AND APOS-THEORY IN ELECTRICAL ENGINEERING

As described in the introduction, there are two aspects to research question RQ 2. They are expressed in sub-questions RQ 2A and RQ 2B. The previous chapter investigated the first aspect based on RQ 2A. It analyzed how students' answers changed when they worked with Tutorials. This chapter focuses on the second aspect described by research question RQ 2B:

RQ 2 was introduced in Section 1.1 (p. 2) and reads:

To what extent can the conceptual difficulties identified before be overcome through the use of existing Tutorial worksheets?

RQ 2B Are there relevant conceptual difficulties that are not addressed by the existing Tutorial worksheets?

To answer this question, the content of relevant existing Tutorials has to be analyzed. Specifically, in this thesis, the Tutorials *Current and Resistance* as well as *Voltage* will be put under scrutiny.

Based on a Tutorial's text alone, it is not possible to identify the conceptual difficulties that the respective Tutorial addresses, as many of the key ideas and relations that students are supposed to take away from a Tutorial are part of the students' answers and not in the printed text. Thus, an intermediate step is required, determining the Intended Observations and Inferences (IOaI) of the respective Tutorial. The IOaI can then be used to identify the concepts that actually are addressed by the Tutorial.

Section 8.1 describes the process used to determine the IOaI, a process similar to the first step in the Decoding the Disciplines (DtD) cycle. Sections 8.2 and 8.3 analyze the IOaI of the Tutorials *Current and Resistance* as well as *Voltage*, respectively, providing answers to RQ 2B. These sections also present revised versions of the two Tutorials. After a summary, Section 8.5 provides an outlook how the IOaI could be further used to create a genetic decomposition of the Tutorials, allowing for a possible revision based on APOS-Theory.

DtD was introduced in Section 2.4 (p. 34).

8.1 DETERMINING THE INTENDED OBSERVATIONS AND INFERENCES OF TUTORIALS

As the name suggests, the IOaI are the critical observations students are supposed to make when working through a Tutorial as well as the inferences they are supposed to derive from their observations. The IOaI often take the form of short factual statements and rules and also include key facts and relations presented in the info boxes of the Tutorial. Since they describe what a student is supposed to recognize

The IOaI of several Tutorials are listed in full in Appendix C (p. 371).

and learn when working through a particular Tutorial, the IOaI are similar to learning goals used in instructional design. The importance of individual observations and inferences differs strongly and cannot be inferred from features such as their length. In this document, the most important IOaI are therefore printed in red font.

The IOaI are not intended to be sample solutions, but rather represent the author's intent of the questions and info boxes. The phrasing of each observation and inference only represents one possible way to answer a given question or describe a key idea. When working on a Tutorial, students are not expected to give answers with the same wording or even in the same style as the IOaI.

The use of sample solutions for Tutorials was discussed in Section 2.3.4.1 (p. 27).

The IOaI of the Tutorials *Current and Resistance* as well as *Voltage* were determined in three steps:

First, the IOaI were worded. While working through each Tutorial, the author of this thesis created a first draft of the IOaI that fulfilled the description above. He checked this first draft with C. Kautz, who had worked in the Physics Education Group (PEG) at University of Washington, and had partial knowledge of the intents of the Tutorials' original authors. The inclusion of C. Kautz helped the IOaI respect the original authors' intents. When finished, this first draft was presented to E. Dubinsky, an experienced educational researcher with a strong background in mathematics, but no prior knowledge of electrical engineering. His role was the same as that of an interviewer in a decoding interview (see Section 2.4.2). He ensured that the IOaI were intelligible to a novice and represented actual answers to the questions in the Tutorial or the summaries of the information presented in the Tutorial. His role was also to verify that each observation and inference could be reached by students based on general knowledge and logical thinking as well as the text of the Tutorial and the prior IOaI. Based on E. Dubinsky's feedback, the IOaI were revised several times until the document satisfied all involved parties.

APOS-Theory, pioneered by E. Dubinsky, was introduced in Section 2.5 (p. 39).

In a second step, the completeness of the IOaI was verified. E. Dubinsky described what he had understood of the fundamentals of electrical engineering based on the IOaI of the Tutorials. The author of this thesis and C. Kautz checked that no key idea that students were intended to learn through the Tutorials was missing.

Finally, the importance of each individual observation and inference was discussed. The IOaI considered most important were marked as such. These marks were later used to decide which question could be removed from a Tutorial with minimal negative effect for the students.

The IOaI form the basis for an analysis of a Tutorial, as they explicitly state which ideas, concepts, and relations students are supposed to take away from it. The following two sections use the IOaI of the Tutorials *Current and Resistance* as well as *Voltage* to identify relevant conceptual difficulties that were not covered by these two Tutorials.

8.2 the tutorial "current and resistance"

This section presents an in depth analysis and refinement of the Tutorial *Current and Resistance* as published in the *Tutorien zur Elektrotechnik* (Kautz, 2010). Several aspects of the Tutorial will be discussed based on the text of the Tutorial as well as its IOaI. Improvements are proposed that result in an updated version of the Tutorial. This updated version is then analyzed in Section 8.2.7.

The original version of the Tutorial and a description of its history can be found in Appendix B.1 (p. 309)

The IOaI of the original version of the Tutorial are listed in Appendix C.1 (p. 371).

The updated version of the Tutorial is shown in Appendix B.2 (p. 319).

The IOaI of the updated version of the Tutorial are listed in Appendix C.2 (p. 373).

8.2.1 *Description of the Tutorial*

The Tutorial *Current and Resistance* is designed to introduce students to the topic of electric circuits. In the English *Tutorials in Introductory Physics* (McDermott and Shaffer, 2002) and their German translation *Tutorien zur Physik* (McDermott and Shaffer, 2009) it is the first Tutorial on the topic of electric circuits. It is also the first worksheet in the German book *Tutorien zur Elektrotechnik* (i. e. *Tutorials in Electrical Engineering*, Kautz, 2010).

The Tutorial *Current and Resistance* forms one unit with the Tutorials *Voltage* and *Multiple Batteries*. These three Tutorials guide students to build *a model for circuits*. This model is a set of simple rules that students construct based on their observations. These observations are based on simple circuits, built out of batteries, bulbs, and wires. The three Tutorials require no prior knowledge of electrical engineering or electric circuits and are designed so they can be used before any formal instruction. As the name indicates, the first Tutorial introduces the concepts of current and resistance. The concept of voltage is only introduced in the second Tutorial.

8.2.2 *Explicit Inclusion of* KCL

In the following, two different use cases for Kirchhoff's Current Law (KCL) will be differentiated. The multi-wire case, where KCL is applied at a node that connects three or more wires, and the two-wire case, where KCL is applied between two circuit elements connected in series. Although the two-wire case is just special case of the multi-wire use, it is not always considered as such by students. In fact, it will be shown that some consider these two cases to be fundamentally different. It will also be shown that the Tutorial *Current and Resistance* uses the two-wire case to address the misconception of current being "used up", but simply assumes students to have a correct understanding of KCL in the multi-wire case. The misconception of current being an intensive property will also be discussed. Finally, a modification to the Tutorial is presented that lets students observe KCL in the multi-wire case to address the misconception of current being an intensive property.

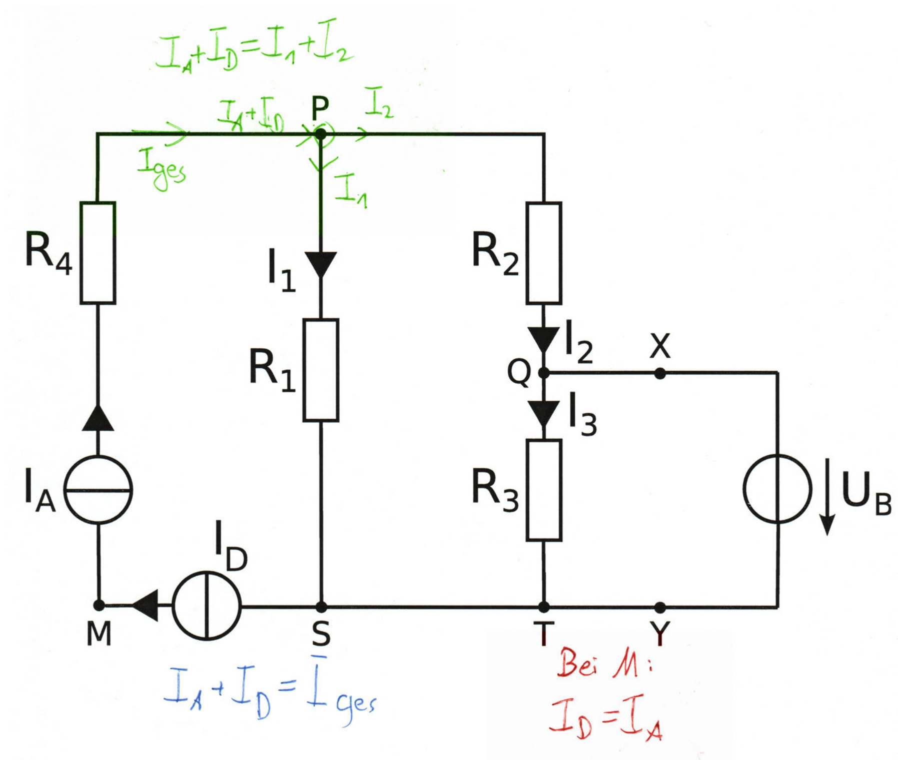


Figure 8.1: Student's notes from an interview on KCL and current sources connected in series. To improve readability, the image was retouched slightly and notes written at different points in time were colored differently. The German "Bei M:" means "At M:".

8.2.2.1 *The Two-Wire and Multi-Wire Case of KCL*

In the multi-wire case, when KCL is applied at a node connecting three or more wires, Kirchhoff's Current Law states that current splits or recombines at that node, with the amount of current flowing into the node being the same as the amount of current flowing out of that node. KCL can also be applied at a node that only has two connecting wires. Again, the law states that current splits or recombines at that node, with the amount of current flowing into the node being the same as the amount of current flowing out of that node. With only two wires connected to the node, the current flowing into the node from one wire must be flowing out of the node through the other wire. Thus, in the two-wire case, when KCL is applied between two elements connected in series, Kirchhoff's Current Law states that the current through both elements is the same. Current is not "used up".

The misconception of current being "used up" is also discussed in Section 7.1 (p. 106).

While a point between two elements connected in series can simply be considered a node connecting two wires, it is not necessarily seen as such by students. A student in interviews described in Appendix F explicitly distinguished both cases. When analyzing the circuit shown in Figure 8.1, the student incorrectly believed that the source currents of the two current sources connected in series would add up to a total current, i. e. $I_A + I_D = I_{ges}$[1] (see blue text in Figure 8.1). To investigate if this student had an incorrect understanding of current sources or incorrectly understood KCL, the student was prompted to analyze the current at node P in the circuit. They wrote KCL for node P as $I_A + I_D = I_1 + I_2$ (see green text in Figure 8.1). This equation would be correct if the current through the branch of R_4 were considered to be $I_A + I_D$. The student also correctly described KCL for node Q as the current I_2 splitting into I_3 and the current through voltage source U_B. Consequently, the student was able to correctly apply KCL at nodes that connect three wires. It is likely they would also correctly apply KCL to nodes with more than three wires.

Some misconceptions regarding ideal sources are discussed in Section 7.3 (p. 127).

When asked to apply KCL at node M, i. e. in between the two current sources, the student correctly found that $I_D = I_A$ (see red text in Figure 8.1). When prompted, the student noticed that their belief of the source currents adding up ($I_A + I_D = I_{ges}$) and KCL at M ($I_D = I_A$) were in conflict with each other. After some consideration, the student confirmed their belief that KCL applied to the multi-wire case: "The logical use for KCL is at a node with more than two branches exiting."[2] The student also understood that KCL could be applied at any point on a wire, resulting in the two-wire case: "I could put a node at any point of [the] branch [at left] and apply the node equation there. Then I would always [...] come to the conclusion that the incoming current is equal to the outgoing current, thus would get a trivial equation."[3] However, the student doubted the validity of this application of KCL: "Based on KCL, $I_D = I_A$ is correct. But I am unsure if it is permissible to apply KCL in such a case."[4] The student strongly believed that the currents of the current sources would add up. Thus, KCL could not be applied to the two-wire case: "I would give [...] myself a restriction in $I_A + I_D = I_{ges}$ [...] that I would like to avoid. Thus, I would discard this equation."[5] The student then crossed out the equation $I_D = I_A$ in Figure 8.1.

To confirm the student's understanding of KCL in the two-wire and multi-wire case, they were presented an impromptu task on that topic. The student was presented with the circuit shown in Figure 8.2 and told that both current sources supplied 2 A and the rectangles repre-

1 The letters "ges" are the abbreviation of "gesamt", the German word for "total".

2 German original: "Der logische Anwendungspunkt von der Knotengleichung ist ja an einem Knoten mit mehr als zwei Zweigen, die austreten."

3 German original: "Ich könnte ja an jedem beliebigen Punkt dieses Zweiges einen Knoten setzen und da die Knotengleichung aufstellen. Da würde ich immer [...] auf den Fall kommen, dass der eintretende Strom gleich der austretende Strom ist, also eine triviale Gleichung bekäme."

4 German original: "Nach der Knotenregel [...] ist diese Knotengleichung ($I_D = I_A$) [...] richtig! Allerdings ist meine Frage ob das [Aufstellen der Knotengleichung] so zulässig ist."

5 German original: "weil ich ja damit [...] mir eine Einschränkung in $I_A + I_D = I_{ges}$ gebe [...], die ich vermeiden möchte. Dementsprechend würde ich diese Gleichung hier streichen."

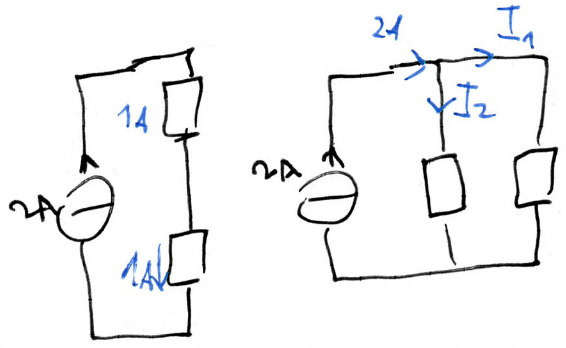


Figure 8.2: Impromptu task on the two different applications of KCL from one of the interviews described in Appendix F. The scan was retouched to improve readability.

sented identical resistors. As can be seen by the student's blue marks, they believed that the current would split evenly between the two resistors connected in series. With this answer, the student again ignored KCL in the two-wire case. In the multi-wire case in the circuit at right in Figure 8.2, the student correctly applied KCL, stating that the 2 A from the source would split into I_1 and I_2, based on the resistance of the two branches. The current arrow next to the bottom resistor in the circuit at left, which is drawn like a voltage arrow is usually drawn, suggests that the students at this point confused properties of current and voltage in series connections. A third task that is not shown here would support this interpretation. Nevertheless, the student again correctly applied KCL in the multi-wire case, while they did not in the two-wire case.

8.2.2.2 *KCL in the Two-Wire Case in the Tutorial*

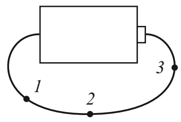
As the student from the interview clearly differentiated between the two-wire and multi-wire case of KCL, it is reasonable to also consider the two cases separately when analyzing the introduction of KCL in the Tutorial *Current and Resistance*.

At two points in the Tutorial, students investigate the two-wire case of KCL. The respective tasks are shown in Figure 8.3. Task 1.2 (at the top of Figure 8.3) intends students to observe: "If a wire is connected to a battery to form a closed circuit, the current is the same everywhere in the wire and through the battery" (see Appendix C.1). Task 2.1 (at the bottom of Figure 8.3) presents students with a series connection of two identical bulbs that light up equally bright. Task 2.1.a then explicitly addresses the idea of current being "used up". It intends students to observe: "Current is not 'used up'" (see Appendix C.1).

The misconception of current being "used up" is discussed in Section 7.1 (p. 106).

1.2 A student has briefly connected a wire across the terminals of a battery. The student finds that the wire seems to be equally warm at points 1, 2, and 3. The battery heats up, too.

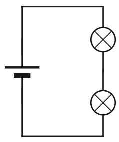
Based on this observation, what might you conclude is happening at the different points in the wire and in the battery?



2 Bulbs in series

Set up a two-bulb circuit with identical bulbs connected one after the other as shown. Bulbs connected in this way are said to be connected *in series*.

2.1 Compare the brightness of the two bulbs with each other. Pay attention only to large differences in brightness. You may notice minor differences, if two "identical" bulbs are, in fact, not quite identical.



Use your observations and the assumptions we have made in developing our model for electric current after Part 1.4 to answer the following questions:

a. Is current "used up" in the first bulb or is the current the same through both bulbs?

Figure 8.3: Two tasks in the original version of the Tutorial *Current and Resistance* that address current being "used up".

8.2.2.3 *The Multi-Wire Case and Current as an Intensive Property*

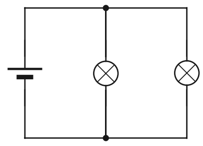
In contrast to the two-wire case, the multi-wire case of KCL is not addressed in the Tutorial. Instead, in the section "Bulbs in parallel" (Figure 8.4), students are expected to know the behavior of current at a node. This section discusses the flow of current in a circuit consisting of a battery connected to the parallel connection of two bulbs. Students observe the brightness of the bulbs as equal (task 3.1), infere that the amount of current through both bulbs is equal (task 3.1.a) and are then asked to "describe the current in the entire circuit" (task 3.1.b). As can be seen in Figure 8.5, students are supposed to answer that the current divides at one of the junctions (nodes) and recombines at the other. Students are supposed to apply KCL. Based on this answer, they will discover in the following tasks that batteries are not current sources, but that each branch connected in parallel to a battery is independent of the other branches.

Shaffer and McDermott (1992), the authors of the Tutorial, describe the structure of the Tutorial in one of their papers. According to the authors students "find that the brightness of each [bulb] is the same as that of a single bulb. They infer that the current through each of the parallel branches is equal to the current through the single bulb and deduce that the current through the battery must be greater." The intended outcome is that "[t]he students recognize that the equal brightness of a single bulb and of all identical bulbs connected in parallel across an ideal battery implies that the current through the

3 Bulbs in parallel

Set up a two-bulb circuit with a battery and two identical bulbs so that the terminals of the bulbs are connected with each other. Bulbs connected together in this way are said to be connected *in parallel*.

3.1 Compare the brightness of the two bulbs in this circuit. As before, pay attention only to large differences in brightness. You may notice minor differences, if two "identical" bulbs are, in fact, not quite identical.



a. What can you conclude from your observation about the amount of current through each bulb?

b. Describe the current in the entire circuit. Base your answer on your observations. In particular, where does the current through the battery divide and recombine?

3.2 Compare the brightness of the two bulbs in parallel to the brightness of a single-bulb circuit (with the same battery). As before, pay attention only to large differences in brightness.

Is the current through the battery in a single-bulb circuit *greater than*, *less than*, or *equal to* the current through the battery of a circuit with two light bulbs in parallel? Explain based on your observations.

Figure 8.4: Section "Bulbs in parallel" in the original version of the Tutorial *Current and Resistance*.

battery is not constant but depends on the configuration of the circuit."

The Tutorial has been used for decades and it has been shown multiple times to be more effective in helping students overcome common misconceptions than traditional instruction (see e. g. Section 7.1). Consequently, the approach presented above must work as intended for many students. However, during the development of the IOaI, it was observed that the question shown in Figure 8.4 can be answered incorrectly in a consistent manner, when current is incorrectly considered an intensive property. An intensive property of a material is a property that does not depend on how much of that material is present (Tolman, 1917). Temperature for example is intensive. If a chunk of metal is split in half, the temperature of each of the halves is the same as that of the original chunk. In contrast, an extensive property of a material is dependent on the amount of material. Mass is an example of an extensive property. If the aforementioned chunk of metal were split, the mass of each of its pieces would be less than that of the whole.

When answering task 3.1.b, students who believe current to be an intensive property would likely describe the current to flow from

3.1 Identical bulbs connected in parallel to a battery, are equally bright.

3.1.a Identical bulbs connected in parallel to a battery receive equal current.

3.1.b In a parallel connection, current divides or recombines at junctions.

3.2 Multiple bulbs connected in parallel to a battery are as bright as if they were connected alone. Connecting a second bulb in parallel to a battery does not change the brightness of the first bulb.

Therefore, the current drawn from a battery by a parallel connection of bulbs is greater than that drawn by a single bulb.

Figure 8.5: Excerpt of the IOaI of the original version of the Tutorial *Current and Resistance*.

the battery to one of the nodes, where it would "divide" to the two branches and "recombine" at the other node. They would believe that the (amount of) current through the battery, the left bulb, and the right bulb were the same. While the use of "divide" and "recombine" in task 3.1.b might confuse them, it is highly unlikely that the wording of the task alone could cause them to change their beliefs. In the first part of task 3.2, students observe that bulbs connected in parallel glow as brightly as a single bulb connected to a battery. In the second part of the task, students who believe current to be an intensive property would conclude that "current drawn from a battery by a parallel connection of bulbs is equal to that drawn by a single". A summary box at the end of the section states that "A characteristic of an *ideal* battery is that the branches connected directly across it are independent of another." The summary in this box could be seen as a confirmation of the students' incorrect belief.

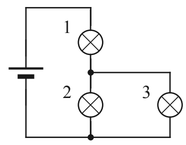
While informal observations of the author indicate that most if not all students at Hamburg University of Technology[6] (TUHH) believe current to be an extensive quantity, Kautz informally observed several workshop participants who seemed to believe current to be an intensive property[7]. McDermott and van Zee (1985) observed that "[m]ost of the college physics students who participated in [their] study lacked a model that could guide them in predicting the relative brightness of bulbs in simple circuits. For example, [...] the students

6 "Technische Universität Hamburg" in German, formerly "Technische Universität Hamburg-Harburg".
7 personal communication

3 Current flow at junctions

Set up a three-bulb circuit with a battery and identical bulbs as shown at right.

3.1 Compare the brightness of the three bulbs in this circuit. As before, pay attention only to large differences in brightness. You may notice minor differences, if two “identical” bulbs are, in fact, not quite identical.



a. What can you conclude from your observation? Compare the current through bulb 1, bulb 2, and bulb 3.

b. Describe the current in the entire circuit. Base your answer on your observations.

Do your observations agree with the idea that all of the current that flows through bulb 1 also flows through bulb 2 and bulb 3?

c. Is it correct to say that “the current is divided” between bulb 2 and bulb 3?

How is this situation different to the one in 2.3.c?

Our observations indicate that the electric current splits and combines at junctions and no “new current is created” or “destroyed”. The flow of electric current is in this regard similar to the flow of water in a system of closed pipes.

This behavior of the electric current is referred to as Kirchhoff’s Current Law.

Figure 8.6: New Section “Current flow at junctions” in the revised version of the Tutorial *Current and Resistance*. The dashed line indicates a page break.

[...] did not seem to envision a current that divides or recombines at branches.” Apparently, McDermott and van Zee (1985) were aware of these student difficulties, but decided to not address them in the *Tutorials in Introductory Physics* (McDermott and Shaffer, 1997). One possible approach to address these difficulties is presented below.

8.2.2.4 *Explicitly Addressing KCL in the Multi-Wire Case*

The full Tutorial is presented in Appendix B.2 (p. 319).

To explicitly address the misconception of current being an intensive property, a new section was added in the revised version of the Tutorial *Current and Resistance*. It is called “Current flow at junctions” and guides students to make an observation that serves as evidence for KCL in the multi-wire case. The section is shown in Figure 8.6. The circuit at the top right of Figure 8.6 is a simplified version of a circuit used later in the same Tutorial. It consists of a battery connected in series with bulb 1, followed by the parallel connection of bulbs 2 and 3. Students are told to build up this circuit and compare the brightness of the three bulbs. They are expected to observe that bulbs 2 and 3 glow equally bright while bulb 1 glows brighter than each of the other two bulbs. Task 3.1.a asks students to relate these observations to the current flowing through the bulbs. As stated on the first page of the Tutorial (see Figure 8.10, p. 192), the brightness of a bulb is an indicator for the current flowing through it. Thus, the current flowing through bulbs 2 and 3 must be equally large. Also, the current through bulb 1 must be larger than that through the other two bulbs.

Based on their analysis of the current through the bulbs, students are asked to "describe the current in the entire circuit". As the current through bulb 1 is larger than that through bulb 2 and that through bulb 3, it is impossible that the same amount of current flows through all three bulbs. This observation clearly contradicts the belief that current is an intensive property. With this task all students are supposed infere that the current has to split at the node between bulbs 1, 2, and 3. Task 3.1.b was added to ensure that students discuss the behavior of the current at the nodes.

As can be seen at the bottom of Figure 8.6, a box was added that reiterates the behavior of the electric current at junctions and connects this behavior with the name Kirchhoff's Current Law (KCL). The *Tutorials in Introductory Physics* (McDermott and Shaffer, 2002) did not contain references to the names of the laws students observed in the Tutorials. The Tutorial *Voltage* in the *Tutorien zur Elektrotechnik* (Kautz, 2010), however, explicitly mentions Kirchhoff's Voltage Law (KVL). Thus, it is fitting that the Tutorial *Current and Resistance* explicitly mentions Kirchhoff's Current Law (KCL). As the circuit used in the section shown in Figure 8.6 was also used in the last section of the Tutorial, slight modifications were made to that section. In particular, as students have now seen the circuit before, it is not necessary to let them predict the brightness of the bulbs.

8.2.3 *Removal of the Dependence on 'Flow'*

The Tutorial *Current and Resistance* introduces students to the concept of electricity by letting them examine the conditions under which a bulb will light (see Figure 8.7). As can be seen from the IOaI (Figure 8.8), the Tutorial lets students discover that a bulb only lights if a closed conducting path exists that contains both the bulb and a battery. Then, a box introduces the idea of *electric current* by stating "A flow exists in a complete circuit from one terminal of the battery, through the rest of the circuit, back to the other terminal of the battery, through the battery and back around the circuit. We will call this flow *electric current*" (bottom of Figure 8.7). As described by the IOaI in Figure 8.8, this box not only introduces students to the *electric*

In this tutorial, we construct a model for electric current that we can use to predict and explain the behavior of simple electric circuits.

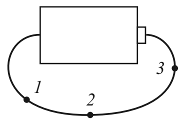
1 Complete circuits

1.1 Obtain a battery, a light bulb, and a single piece of wire. Connect these in a variety of ways and observe whether the bulb lights up or not.

State the requirements for the arrangement of the three elements that must be met in order for the bulb to light.

1.2 A student has briefly connected a wire across the terminals of a battery. The student finds that the wire seems to be equally warm at points 1, 2, and 3. The battery heats up, too.

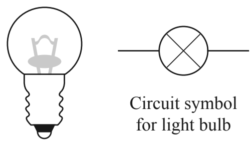
Based on this observation, what might you conclude is happening at the different points in the wire and in the battery?



1.3 Light a bulb using a battery and a single wire. Observe and record the behavior (i. e., brightness) of the bulb when objects made out of various materials are inserted into the circuit. (Try materials such as paper, coins, pencil lead, pens, eraser, etc.)

What is similar about most of the objects that let the bulb light up?

1.4 Carefully examine a bulb. Two wires extend from the filament of the bulb into the base. You probably cannot see into the base, however, you should be able to make a good guess as to where the wires are attached. Explain based on your observations in parts 1.1 through 1.3.



On the basis of the observations that we have made, we will make the following assumptions for our model for the electric current:

- A "flow" exists in a complete circuit from one terminal of the battery, through the rest of the circuit, back to the other terminal of the battery, through the battery, and back around the circuit. We will call this flow *electric current.*
- For identical bulbs, bulb brightness can be used as an indicator of the amount of current through that bulb: the brighter the bulb, the greater the current through it.

Starting with these assumptions, we will develop a model that we can use to account for the behavior of simple circuits. The construction of a scientific model is a step-by-step process in which we make as few assumptions as possible to explain the phenomena under consideration.

Figure 8.7: First page of the original version of the Tutorial *Current and Resistance*.

current, but also states that *current is a flow*. As such – although not necessarily obvious to the students – current has several properties. One of these is KCL. In the following, the meaning of *flow* in physics will be described in detail. This meaning will be contrasted with the word's use in in everyday language. Finally, the changes to the Tutorial worksheet will be analyzed.

8.2.3.1 *Definition of 'Flow'*

Many physics textbooks as e. g. Reese (2000), Resnick et al. (2002), Young and Freedman (2004), and Giancoli (2005) introduce the con-

Excerpt from the IOaI of the Tutorial *Current and Resistance*

1.1 In Order for a bulb to light up, a closed circuit has to exist.

1.2 If a wire is connected to a battery to form a closed circuit, the current is the same everywhere in the wire and through the battery.

1.3 A closed loop does not contain any insulators. The closed loop has to be a closed loop of conductors.

1.4 Bulbs have a conducting path between their two terminals, which allows a bulb to be inserted into a closed loop by attaching wires to each terminal of the bulb. Without this conducting path, the bulbs would not light up.

Box A flow exists in a closed circuit. The thing that flows is called current.

The brighter a bulb glows, the more current flows through it.

Objects which allow current to flow, are called conductors, objects that prevent current from flowing are called insulators.

Figure 8.8: The IOaI of the Tutorial tasks shown in Figure 8.7. All IOaI listed in red were considered very important.

cept of flow not as an independent concept, but only in the context of fluids. Resnick et al. (2002) for example begin describing the flow of fluids by discussing some of its properties. The first of these properties is

> "*Fluid flow can be steady or nonsteady.* We describe the flow in terms of the values of such variables as pressure, density, and flow velocity at every point of the fluid. If these variables are constant in time, the flow is said to be *steady*. The values of these variables will generally change from one point to another, but they do not change with time at any particular point." (Resnick et al., 2002, emphasis in original)

They also define

> "*equations of continuity*, which are in effect conservation laws for mass. The equation of continuity states that if within any volume element of space (*not* volume of fluid) there are no *sources* (where additional matter is introduced into the flow) or *sinks* (where matter is removed from

> the flow), then the total mass within that volume element must remain constant. [...] Equations of continuity are common in physics and appear in any subject in which a flow is involved. For example, there is an equation of continuity for electric charge that is a conservation law for charge rather than mass." (Resnick et al., 2002, emphasis in original)

Thus, a flow in physics can be steady or non-steady, and a steady flow follows the equation of continuity: that what is flowing is neither spontaneously created nor destroyed. By extension, as the electric current is a flow, the electric charge is neither spontaneously created nor destroyed.

8.2.3.2 *'Flow' in Every-Day Language*

If students have not had instruction on the properties of *a flow* in the context of physics, it is likely they will understand the word 'flow' as it is used in every-day language. The different meanings of 'flow' in every-day language are shown in Figure 8.9.

The every-day definition of flow includes the idea of a steady and continuous movement, although not necessarily as strict as in the definition in physics. The conservation of the material that is flowing, however, is not part of the every-day understanding of the word.

8.2.3.3 *Usage of 'Flow' in the Tutorial*

Introducing the electric current *as a flow* in the Tutorial was likely supposed to convey three facts. It (1) emphasized that "something" was happening in the circuit elements that caused the bulbs to glow,

FLOW, verb
: of liquid, gas, or electricity : to move in a steady and continuous way
: to move in a continuous and smooth way
: to move, come, or go continuously in one direction

FLOW, noun
: an act of flowing : the movement of something that is flowing
: a large area of mud or some other material that is flowing or that was formed by flowing
: the amount of something that flows in a certain time

Figure 8.9: Definition of the word 'flow', as provided by Merriam-Webster (2015). Similar definitions can be found in e. g. Morris (1975).

i. e. a current was flowing. It (2) described the current as steady, and (3) characterized the electric current to follow an equation of continuity.

In the introduction of the updated version of the Tutorial (see Figure 8.10), this reference to current being a 'flow' was removed as students most likely did not understand these three facts based on the word 'flow'. Aspect (1) was still addressed by stating that something – the electric current – is flowing through the circuit. This current being steady (2) was not considered so important that it had to be addressed explicitly. Aspect (3) that the electric charges that are flowing are neither created nor destroyed is already addressed through the in-depth analysis of KCL presented above.

Additionally, task 2.1 was added in the updated version of the Tutorial. This task asks students to describe the path of the current in a simple circuit of a battery connected to two bulbs in series. As the task asks students to describe the path of the current, they must actively think about the current flowing through the circuit. Task 2.1 also forms the basis for the discussion of tasks 2.2 and 2.3, where the amount of current flowing through the bulbs in series is discussed, and is analogous to task 3.1.b, where students have to describe the flow of current in a parallel connection.

8.2.4 *The German Word 'teilen' in the Context of Series Connections*

The German *Tutorien zur Elektrotechnik* by Kautz (2010) introduced task 2.2.c (see Figure 8.11) which was not part of the English *Tutorials in Introductory Physics* (McDermott and Shaffer, 2002). The task deals with the usage of the German word 'teilen', which translates as *to share* or *to divide*.

Consider the circuit in the top right of Figure 8.4 (p. 184). The two bulbs can be seen as a current divider connected to a battery. In German, one may say "Die zwei Lampen der Parallelschaltung *teilen* sich den Strom der Batterie.", i. e. "The current from the battery is *divided* between the two bulbs in parallel." Corresponding to this, the German word for 'current *divider*' is 'Strom*teiler*'.

In the case of a series connection of a battery and two bulbs, however, things are more difficult. It is incorrect to say that the current of the battery is *divided* between the two bulbs in series, because the word divided implies that two or more distinct, separate parts are created (Merriam-Webster, 2016a). Contrarily, in a series connection the same current, i. e. the same electric charges and the same amount of current, is flowing through both bulbs.

In German, however, it is not strictly incorrect to say that "Die zwei Lampen der Reihenschaltung *teilen* sich den Strom der Batterie.", i. e. that two bulbs in series "teilen" the current. Unlike the English word 'divide' (see Figure 8.13), the German word 'teilen' (see Fig-

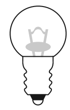
In this tutorial, we construct a model for electric current that we can use to predict and explain the behavior of simple electric circuits.

1 Complete circuits

1.1 Obtain a battery, a light bulb, and a single piece of wire. Connect these in a variety of ways and observe whether the bulb lights up or not.

State the requirements for the arrangement of the three elements that must be met in order for the bulb to light. Which parts of the wire have to be connected to which parts of the bulb and battery?

1.2 Carefully examine a bulb. Two wires extend from the filament of the bulb into the base. You probably cannot see into the base, however, you should be able to make a good guess as to where the wires are attached. Explain based on your observations in part 1.1.

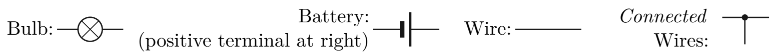


On the basis of the observations that we have made, we will make the following assumptions for our model for the electric current:

- The glowing of a bulb can be explained by an *electric current* flowing through it.
- For identical bulbs, bulb brightness can be used as an indicator of the amount of current through that bulb: the brighter the bulb, the greater the current through it.

Starting with these assumptions, we will develop a model that we can use to account for the behavior of simple circuits. The construction of such a *scientific model* is a step-by-step process in which we make as few assumptions as possible to explain the phenomena under consideration.

The following symbols are used to represent circuit elements in our model:



1.3 Which conditions must be met in order for an electric current to flow in a circuit?

Figure 8.10: First page of the revised version of the Tutorial *Current and Resistance*.

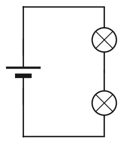
ure 8.14) does not necessarily require that two or more distinct shares are formed. In this sense it is very similar to the word *share* (see Figure 8.12), which also can be used in phrases as “they share a passion for opera”, where the passion is not divided.

In the revised version task 3.1.c was added. Now, students are not only asked if it is correct to say “Strom wird geteilt”, i. e. current is divided/shared, in the case of a series connection, but also in the case of a parallel connection. This change was intended to help students understand the difference between both situations. To further support this, students were asked to compare the usage of the phrase “Strom wird geteilt” in both situations.

2 Bulbs in series

Set up a two-bulb circuit with identical bulbs connected one after the other as shown. Bulbs connected in this way are said to be connected *in series*.

2.1 Compare the brightness of the two bulbs with each other. Pay attention only to large differences in brightness. You may notice minor differences, if two "identical" bulbs are, in fact, not quite identical.



Use your observations and the assumptions we have made in developing our model for electric current after Part 1.4 to answer the following questions:

2.2 Compare the brightness of each of the bulbs in the two-bulb series circuit with that of a bulb in a single-bulb circuit (with the same battery).

c. Why would it be incorrect to say that "the current from the battery is divided" between the two light bulbs in series?

Figure 8.11: Tasks from the Tutorial *Current and Resistance* on the phrase "current is divided" in the context of a series connection.

8.2.5 *Removal of Observations on Closed Circuits*

It was decided to remove tasks 1.2 and 1.3 (see Figure 8.7) in the updated version of the Tutorial. The goal of task 1.2 was for students to discover that the current through a wire is the same at every point in the wire (see Figure 8.8). While this was considered to be very important, the task was not based on an observation the students could make themselves, as that would require short-circuiting a battery which would deplete the battery so fast that it could not be used reliably for the rest of the Tutorial. Additionally, the idea that the

SHARE, verb

1. to divide and distribute in shares : apportion –usually used with *out* <shared out the land among his heirs>
2. a. to partake of, use, experience, occupy, or enjoy with others
   b. to have in common <they share a passion for opera>
3. to grant or give a share in –often used with with <shared the last of her water with us>
4. to tell (as thoughts, feelings, or experiences) to others –often used with with

Figure 8.12: Definition of the verb *share*, as provided by Merriam-Webster (2016b).

DIVIDE, verb

1. a. to separate into two or more parts, areas, or groups <divide the city into wards>
   b. to separate into classes, categories, or divisions <divide history into epochs>
   c. cleave, part <a ship dividing the waves>
2. a. to separate into portions and give out in shares : distribute <divide profits>
   b. to possess, enjoy, or make use of in common <divide the blame>
   c. apportion <divides her time between the office and home>
3. a. to cause to be separate, distinct, or apart from one another <fields divided by stone walls>
   b. to separate into opposing sides or parties <the issues that divide us>
   c. to cause (a parliamentary body) to vote by division

Figure 8.13: Excerpt of the definition of the verb *divide*, as provided by Merriam-Webster (2016a).

TEILEN, verb

1. a. ein Ganzes in Teile zerlegen
   b. eine Zahl in eine bestimmte Anzahl gleich großer Teile zerlegen; dividieren
   c. sich aufspalten, in Teile zerfallen
2. a. (unter mehreren Personen) aufteilen
   b. etwas, was man besitzt, zu einem Teil einem anderen überlassen
3. ein Ganzes in zwei Teile zerteilen
4. a. gemeinsam (mit einem anderen) nutzen, benutzen, gebrauchen
   b. gemeinschaftlich mit anderen von etwas betroffen werden; an einer Sache im gleichen Maße wie ein anderer teilhaben

Figure 8.14: Excerpt of the Definition of the German verb *teilen*, as provided by Duden (2016).

current is the same everywhere in a wire is a variation of the observation that two bulbs in series glow equally bright, which is discussed in detail in the Tutorial.

As can be seen in Figure 8.8 task 1.3 was not considered to be very important. This task dealt with the conductivity of different materials, an aspect of electricity that is not relevant for electric circuits that are based on singular, ideal circuit elements.

8.2.6 *Addition of Circuit Elements*

In the updated Tutorial, the info box on the first page was extended to explicitly introduce the circuit symbols for a battery, a wire, and the connection of two or more wires. The previous version of the Tutorial had only introduced the circuit symbol for a bulb. This obvious inconsistency in the old version of the Tutorial was one of the issues that were only discovered by an external observer, in this case E. Dubinsky.

8.2.7 *Analysis of the Revised Tutorial*

The revised version of the Tutorial has been used in the course EE1ME from 2014 onward. Observations made during the usage of the Tutorial and feedback from students will be presented below. Thereafter, a post-test used to evaluate the Tutorial will be presented. After a discussion of the test's results the revised version will be evaluated.

In the winter semester 2014 the Tutorial *Current and Resistance* was used in the first recitation session of the semester, which took place within seven days after the first lecture. In the winter semester 2015 the Tutorial was used in the second recitation session of the semester, thus about 8-14 days after the first lecture. Both times, the Tutorial's subject matter was presented to students in lecture before the Tutorial.

An overview of when tests and Tutorials were used in the respective courses is provided in Appendix A (p. 305).

8.2.7.1 *Complexity of the Tutorial's Language*

Students and teaching assistants (TAs) alike have often remarked that many tasks in the Tutorials use complicated language. In a TA training, one TA specifically named the revised Tutorial *Current and Resistance* as an example.

The German language tends to have longer and more convoluted sentences than English. Thus, part of the blame can be attributed to the German language and likely is unavoidable. Still, some of the complexity is due to tasks having become more specific over time. In the *Tutorials in Introductory Physics* (McDermott and Shaffer, 2002), task II.B.2 of the Tutorial *Current and Resistance* reads:

> "How does the current through a bulb in a single-bulb circuit compare with the current through the same bulb when it is connected in series with a second bulb? Explain."

In the German Translation (McDermott and Shaffer, 2009), the task now labeled 2.2.b explicitly lists three answering options. Translated back into english, it reads:

> "Is the current through the light bulb of a single-bulb circuit *greater than*, *less than*, or *equal to* the current through the same bulb when it is connected in series with a second bulb? Explain."[8]

The original task asked students to compare the currents, while the translated task asks students if the current is *greater than*, *less than*, or *equal*. When reading these three options, the problem-setup has not been fully stated. Thus, to process the question, the reader has to hold these three options in their memory until the end of the question. Only then they can start to think of the answer. This complexity is not present in the English original, which in turn does not specify the detail required in the answer. While this missing specificity might be criticized, students who regularly work with Tutorials will likely learn how specific their answers are supposed to be.

8.2.7.2 *Feedback on "Divide Current"*

The question discussed here is described in Section 8.2.4 (p. 191).

One TA also remarked that students had trouble with task 2.3.c in the Tutorial *Current and Resistance*, where they are asked "Why would it be incorrect to say that [in a series connection of a battery and two bulbs] the current from the battery is divided between the two light bulbs in series?". The TA used the water analogy and stated that if water flows through a pipe with several stages, e. g. two small basins with an inflow and an outflow, many students would still say the water is divided into the basins – even when the water has not been divided in separate parts. In this example the TA used the German word "teilen".

This statement hints that the task's learning goal was not reached for the students and, most likely, neither the TA. The goal of task 2.3.c is to help students realize that the word "teilen" in the context of circuit elements in series may convey unintended and inappropriate connotations. The word "teilen" is strongly connected to parallel connections and current dividers and would, because of that, never be used by a professional in the context of a series connection. However, the task argues that the use of the word "teilen" is incorrect due to

8 German original: "Ist der Strom durch die Glühlampe in einer Schaltung mit einer einzelnen Lampe *größer*, *kleiner* oder *gleich* dem Strom durch dieselbe Glühlampe, wenn diese mit einer weiteren Lampe in Reihe geschaltet ist? Begründen Sie."

physics, instead on focusing on the *convention* to only use "teilen" in a certain context.

8.2.7.3 *Description of the Post-Test*

Two tests were used to investigate the effect of the revised version of the Tutorial *Current and Resistance* in the course EE1ME. As the Tutorial was used in the first recitation section, right at the start of the course, it was not possible to conduct a pre-test. Consequently, both tests were post-tests conducted several weeks after the Tutorial. The test shown in Figure 8.15 was administered in week 6 of the course EE1ME in 2014. The test shown in Figure 8.16 was administered in week 4 of the course EE1ME in 2015 and for reference also in week 6 of the course EE1EE. At the time of the respective tests, the two Tutorials *Current and Resistance* as well as *Voltage* had been used in the course EE1ME. The course EE1EE is taught traditionally and did not use any Tutorials.

Relevant for the evaluation of the Tutorial are those parts of the circuits in Figures 8.15 and 8.16 that are identical in both tests, i. e. the two batteries and the network of bulbs 1 to 5. These five bulbs are arranged to allow the investigation of the two-wire and the multi-wire case of KCL. By brightness, they are ranked $B_1 = B_5 > B_4 > B_2 = B_3$. Based on KCL, the currents are $I_1 = I_3 + I_4$.

The two cases of KCL are differentiated in Section 8.2.2 (p. 179).

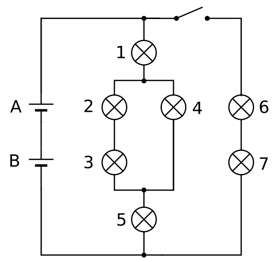
The two-wire case of KCL, i. e. the current through two circuit elements in series being the same, can be investigated by comparing bulbs 2 and 3 and by comparing bulbs 1 and 5. Bulb 2 is connected directly in series with bulb 3 and thus presents the most basic test for the two-wire case and the related misconception that current is "used up". This circuit configuration is also used in the five-bulbs test and, crucially, the Tutorial (see e. g. Figure 8.11). Thus, students who correctly indicate $B_2 = B_3$, could have understood that current is not "used up" – or simply *remember* that bulbs in series glow equally bright. An alternative test for the two-wire case is the comparison of bulbs 1 and 5. While these bulbs are not connected to each other directly, they are connected in series. Between these two bulbs is the network of bulbs 2, 3, and 4, which can be treated as one component. Thus, the circuit consists of a series connection of bulb 1, the network of bulbs 2 to 4, and bulb 5. Such a configuration of bulbs was not used in the Tutorial, so that teaching to the test can be excluded. Students who assume current is "used up", would likely indicate $B_5 < B_1$ or $B_1 < B_5$, depending on whether they used the technical or the physical direction of current.

The five-bulbs test is discussed in Section 8.2.2 (p. 179).

The multi-wire case of KCL, i. e. current splitting according to KCL at nodes with three or more wires attached, is covered in two ways in the post-tests. Firstly, the brightness of bulbs 1 and 4 is compared. Students might believe that the current from bulb 1 splits into two currents and that both of these currents are equal to the current through

Task 1

The circuit at right contains the identical bulbs 1 to 7 and the identical batteries A and B. The batteries can be treated as ideal voltage sources, i.e. their internal resistance is zero.



At first, the switch is in the open position.

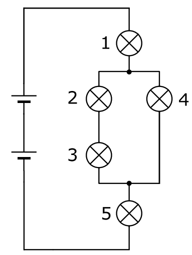
1. Rank bulbs 1 to 5 according to their brightness. Use the relational operators >, < and =. If a bulb does not glow at all, state this explicitly.

Explain briefly.

Figure 8.15: Post-test for the revised version of the Tutorial *Current and Resistance* used in the course EE1ME in 2014.

Task 1

The circuit at right contains identical bulbs and ideal batteries. (The batteries can be treated as ideal voltage sources, i.e. their internal resistance is zero.)



a) Rank all bulbs by their brightness. If two bulbs glow equally bright or a bulb does not glow at all, state this explicitly. Use the relational operators >, <, and =.

Explain briefly.

b) The currents through bulbs 1, 3, and 4 are measured using a current meter. The currents are denoted by I_1, I_3, and I_4, respectively. What is their relation?

☐ $I_1 < I_3 + I_4$ ☐ $I_1 = I_3 = I_4$ ☐ I am not sure.
☐ $I_1 > I_3 + I_4$ ☐ $I_1 = I_3 + I_4$

Explain briefly.

Figure 8.16: Post-test for the revised version of the Tutorial *Current and Resistance* used in the course EE1ME and, for reference, in EE1EE in 2015.

Table 8.1: Frequency of correct statements regarding the two-wire and multi-wire case of KCL in the tests shown in Figures 8.15 and 8.16.

			two-wire case		multi-wire case	
Course	Week	N	$B2 = B3$	$B1 = B5$	$B1 \neq B4$	$I1 = I3 + I4$
EE1ME, 2014	6	135	82 %	78 %	90 %	
EE1ME, 2015	4	274	88 %	81 %	97 %	50 %
EE1EE, 2015	6	200	73 %	71 %	96 %	75 %

bulb 1. These students would likely indicate $B1 = B4$. Secondly, the node rule at the node below bulb 1 is tested explicitly. In task 1 b) in Figure 8.16, students are asked to compare the current through bulbs 1, 3, and 4. To prevent students from blindly applying the equation for KCL, the currents were not marked in the circuit and students are asked to compare $I1$, $I3$, and $I4$ instead of $I1$, $I2$, and $I4$.

8.2.7.4 *Results of the Post-Tests*

Table 8.1 provides an overview of the frequencies of several correct statements from the tests.

In each test, the correct relation $B2 = B3$ was stated more often than the relation $B1 = B5$. This was no surprise, as students already were familiar with the configuration of bulbs 2 and 3. The difference in the frequency of these two statements is not large in any of the tests, which could indicate that students have generally understood that current is not "used up". This possibility is discussed below. These results also support the assumption that teaching to the test did not play a large role in the five-bulbs test. Compared to the students in EE1EE, the students in EE1ME performed better, even though the students in EE1EE can be considered more proficient and had two more weeks of instruction.

Teaching to the test in the context of the five-bulbs test is discussed on p. 117.

The fraction of students who indicated $B1 \neq B4$, i. e. who correctly applied KCL in the multi-wire case, was higher than the fraction of students who indicated $B1 = B5$, i. e. who correctly applied KCL in the two-wire case. Again, this result is not surprising. The belief that current at a junction would behave as an intensive property is rare, while the belief that current is "used up" is quite common. The students in EE1EE and EE1ME performed about the same in 2015.

The misconception of current being an intensive property is described on p. 184.

Surprisingly, in EE1ME only 50% and in EE1EE only 75% of students correctly stated that $I1 = I3 + I4$. 29% and 19% of students, respectively, stated that $I1 > I3 + I4$. Thus, in both courses, a considerable fraction of students was not able to correctly apply KCL when asked about the currents $I1$, $I3$, and $I4$. One possible explanation is that students believed some of the current from bulb 1 was "used up" by bulb 2 before it reached bulb 3. As one student explained:

Table 8.2: Comparison of correct and incorrect student answers for the two-wire and the multi-wire case of KCL in the courses EE1ME and EE1EE in the test shown in Figure 8.16.

(a) EE1ME, N = 274

	two-wire	
multi-wire	$B_2 = B_3$	$B_2 \neq B_3$
$I_1 = I_3 + I_4$	45 %	6 %
$I_1 \neq I_3 + I_4$	43 %	7 %

(b) EE1EE, N = 200.

	two-wire	
multi-wire	$B_2 = B_3$	$B_2 \neq B_3$
$I_1 = I_3 + I_4$	50 %	17 %
$I_1 \neq I_3 + I_4$	16 %	10 %

> "At the node, the current splits to the other branches. However, some current is used up by bulb 2, thus $I_1 > I_3 + I_4$."[9]

The explanation quoted above can explain some of the incorrect statements. However, 17% (EE1ME) and 7% (EE1EE) of students correctly ranked $B_2 = B_3$ but still answered $I_1 > I_3 + I_4$. Many did not state that current was "used up", but instead gave answers such as:

> "$I_1 = I_2 + I_4$, but I_3 only comes after I_2. $\Rightarrow I_1 > I_3 + I_4$"[10]

This student likely does believe that current is "used up", but has learned that bulbs in series are equally bright and that the phrase "used up" is incorrect.

Another incorrect reasoning for $I_1 > I_3 + I_4$ with $B_2 = B_3$ was often abbreviated to the equation $I_1 = I_2 + I_3 + I_4$. Some students were more elaborate:

> "The current flowing through (bulb) 1 is cut into halves by the parallel connection. After that comes a series connection at bulb 2 and bulb 3 and the half of the current which was created at the parallel connection is divided at bulb 2 and bulb 3. I. e. $(B_2 + B_3 + B_4 = B_1)$ $I_2 + I_3 + I_4 = I_1$."[11]

Misconception: *KCL applies to the currents of circuit elements, not branches connected to the node.*

The student ranked the bulbs as $B_1 = B_5 > B_4 > B_2 = B_3$. They correctly applied KCL to the two-wire case, but not the three-wire case. This explanation reveals the misconception that KCL applies not to the currents of the branches connected to the respective node, but to the currents through circuit elements. This misconception is not addressed in the Tutorials.

9 German original: "Der Strom teilt sich am Knoten auf die weiteren Verzweigungen auf. Jedoch wird durch Lampe 2 Strom verbraucht, wodurch $I_1 > I_3 + I_4$."
10 Original German transcript: $I_1 = I_2 + I_4$, aber I_3 ist hinter I_2 geschaltet. $\Rightarrow I_1 > I_3 + I_4$
11 German original: "Der Strom der durch 1 fließt wird halbiert, durch Parallelschaltung. Darauf folgt eine Reihenschaltung bei L2 und L3 und der halbierte Anteil des Stroms, welcher durch die Parallelschaltung entstand, teilt sich bei L2 und L3 auf. D. h. $(L_2 + L_3 + L_4 = L_1)$ $I_2 + I_3 + I_4 = I_1$."

While students in EE1ME performed better in the bulb rankings, students in EE1EE performed better in the comparison of the currents I_1, I_3, and I_4. This difference can be further investigated using Table 8.2, which compares the correct ($B_2 = B_3$) and incorrect ($B_2 \neq B_3$) answers regarding the two-wire case of KCL to the correct ($I_1 = I_3 + I_4$) and incorrect ($I_1 \neq I_3 + I_4$) answers regarding currents in the multi-wire case. As can be seen, there is a correlation between the correct answers in the course EE1EE, while there is none in EE1ME. The missing correlation could indicate that students in EE1ME have learned that two bulbs in series are equally bright, but still have misconceptions regarding KCL.

For the rankings of the bulbs, students in the course EE1ME performed better than the students in the course EE1EE. As the students in EE1ME do not major in electrical engineering and had two weeks less of instruction, their better performance is likely a result of the Tutorial(s). However, their weaker performance regarding the relation of the currents could indicate that they still have a disadvantage when asked to apply their knowledge outside of the context of the Tutorials.

8.3 THE TUTORIAL "VOLTAGE"

This section presents an analysis and revision of the Tutorial *Voltage*. The version of the Tutorial that is analyzed here is named the *original version* in this work. It was used in the course EE1ME up to 2013 and is a shortened version of the one published in the German *Tutorien zur Elektrotechnik* (Kautz, 2010). That version, in turn, is based on the version used in the *Tutorien zur Physik* (McDermott and Shaffer, 2009) and *Tutorials in Introductory Physics* (McDermott and Shaffer, 2012).

The original version of the Tutorial and a description of its history can be found in Appendices B.3 (p. 331) and B.4 (p. 331)

The IOaI of the original version of the Tutorial are listed in Appendix C.4 (p. 376).

The updated version of the Tutorial is shown in Appendix B.5 (p. 341).

The IOaI of the updated version of the Tutorial are listed in Appendix C.5 (p. 378).

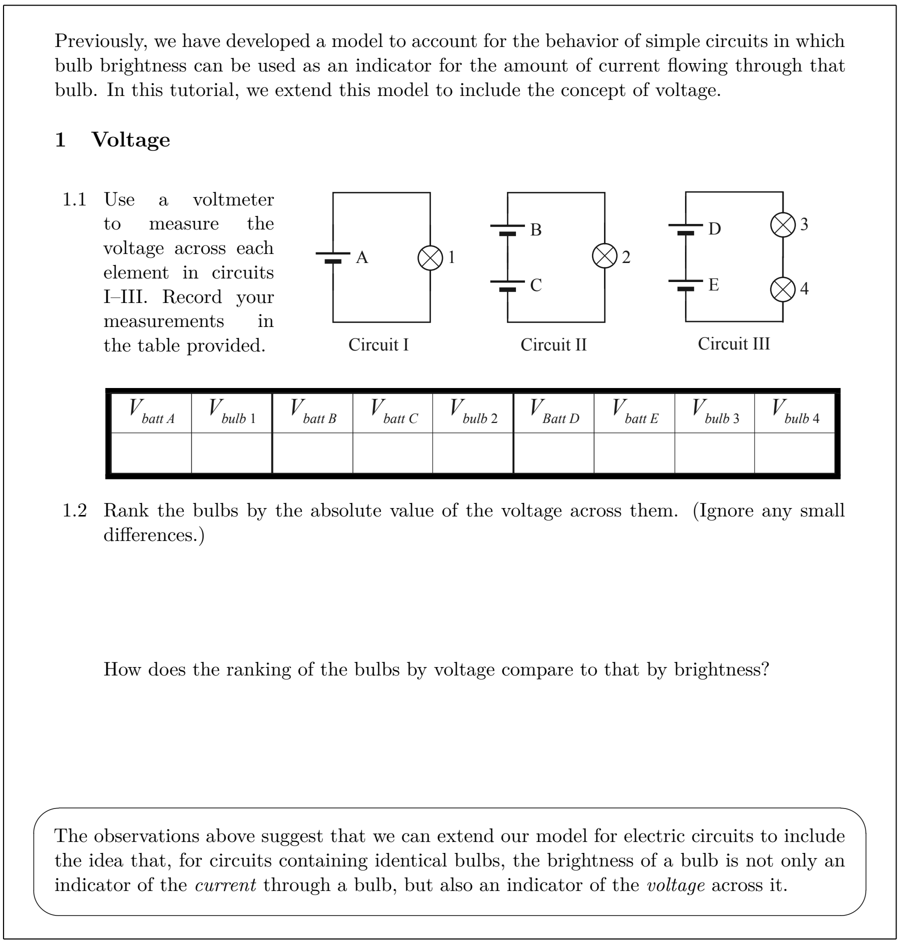
The Tutorial *Voltage* is part two of a series of three Tutorials that build *a model for circuits*. It introduced students to the concept voltage and builds on the concepts of *Current and Resistance* that had been developed in the first Tutorial (see Section 8.2).

8.3.1 *Changes made to the Tutorial "Voltage"*

This section describes three changes to the Tutorial that were made based on the IOaI of the Tutorial.

8.3.1.1 *Bulb Brightness as an Indicator for Current and Voltage*

The start of the original version of the Tutorial is shown in Figure 8.17. Students are asked to measure the voltages in circuits I to III. They observe that the brightness of a bulb is an indicator for the voltage across it. A box then summarizes that the brightness of a bulb is not only an indicator for the current through it, but also for the voltage



Previously, we have developed a model to account for the behavior of simple circuits in which bulb brightness can be used as an indicator for the amount of current flowing through that bulb. In this tutorial, we extend this model to include the concept of voltage.

1 Voltage

1.1 Use a voltmeter to measure the voltage across each element in circuits I–III. Record your measurements in the table provided.

$V_{batt\ A}$	$V_{bulb\ 1}$	$V_{batt\ B}$	$V_{batt\ C}$	$V_{bulb\ 2}$	$V_{Batt\ D}$	$V_{batt\ E}$	$V_{bulb\ 3}$	$V_{bulb\ 4}$

1.2 Rank the bulbs by the absolute value of the voltage across them. (Ignore any small differences.)

How does the ranking of the bulbs by voltage compare to that by brightness?

The observations above suggest that we can extend our model for electric circuits to include the idea that, for circuits containing identical bulbs, the brightness of a bulb is not only an indicator of the *current* through a bulb, but also an indicator of the *voltage* across it.

Figure 8.17: Start of the original version of the Tutorial *Voltage*.

across it. This box effectively *tells* students how current and voltage are related in bulbs.

Instead, the version of the Tutorial published in the German *Tutorien zur Elektrotechnik* (Kautz, 2010) as well as the English *Tutorials in Introductory Physics* (McDermott and Shaffer, 2012) starts with an introductory section allowing students to revisit key findings about the relation between current and resistance. The third section of that Tutorial is identical to the Section 1 shown in Figure 8.17. As in the original version, students are only told the relationship between voltage and current in bulbs.

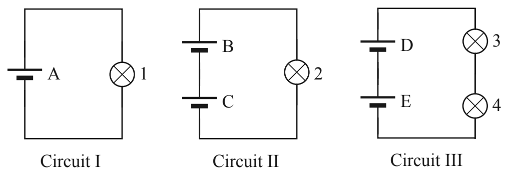
Some of the old tasks were re-introduced in the revised version of the Tutorial (see Figure 8.18). Students now first rank the bulbs in circuits I to III by the current through them. They then measure the voltage across each bulb and rank the voltages accordingly. Finally, the second part of task 1.5 asks students to compare the ranking by current with that by voltage. Instead of simply telling students that the brightness of a bulb is an indicator for both its current and voltage, the Tutorial now lets them discover the relation between a bulb's current and voltage based on their observations. Based on the IOaI of

Previously, we have developed a model to account for the behavior of simple circuits in which bulb brightness can be used as a measure for the amount of current flowing through that bulb. In this tutorial, we extend this model to include the concept of voltage.

1 Voltage

Ask a tutorial instructor to hand you the circuits I through III shown at right.

Examine the brightness of the bulbs.



1.1 Rank the bulbs by the amount of current flowing through them. State explicitly, if the current through two bulbs is the same. Explain how you can rank the bulbs without using an ampere meter.

1.2 Assume a battery in a circuit is replaced by two batteries in series. Does the current through the circuit *increase*, *decrease*, or *stay the same*? Explain.

Our observations suggest that batteries can be considered the "motor" of a circuit that causes current to flow. We will examine this idea further.

1.3 Use a voltmeter to measure the voltage across each element in circuits I–III. Record your measurements in the table provided.

$V_{batt\,A}$	$V_{bulb\,1}$	$V_{batt\,B}$	$V_{batt\,C}$	$V_{bulb\,2}$	$V_{Batt\,D}$	$V_{batt\,E}$	$V_{bulb\,3}$	$V_{bulb\,4}$

1.4 Use a voltmeter to measure the voltage across three wires of your choice. Generalize your findings.

1.5 Rank the bulbs by the absolute value of the voltage across them. Ignore any small differences.

How does the ranking of the bulbs by voltage compare to the ranking by current?

The observations above suggest that we can extend our model for electric circuits to include the idea that, for circuits containing identical bulbs, the brightness of a bulb is not only an indicator of the *current* through a bulb, but also an indicator of the *voltage* across it.

Figure 8.18: Start of the revised version of the Tutorial *Voltage*. The dashed line indicates a page break.

the Tutorial, the current–voltage relation of bulbs is an important part of the Tutorial. This relation should be emphasized more in the Tutorial, possibly by adding a question that lets students explicitly state

1.10 Take the following the circuit elements and connect them individually to a voltmeter. What does the voltmeter read for each element? Do the voltages agree with the ones you measured in circuit I?

Battery:

Bulb:

Wire:

1.11 Answer the following questions, based on the measurements you have done so far. Ignore any small differences.

a. Is the voltage across a *battery* constant or does it depend on the circuit the battery is used in?

b. Is the voltage across a *bulb* constant or does it depend on the circuit the bulb is used in?

c. Is the voltage across a *wire* constant or does it depend on the circuit the wire is used in?

1.13 Examine the labeling of a battery. Do you find any information about voltage or current?

If so, does this agree with your observations so far?

→ Discuss your responses to part 1.11 and 1.13 with a tutorial instructor.

Figure 8.19: New questions on the voltage across specific circuit elements in the revised version of the Tutorial *Voltage*.

the current–voltage relation of bulbs instead of simply informing students about the relation in the box at the bottom of Figure 8.18.

8.3.1.2 *Voltage–Current Relationship for Different Circuit Elements*

The IOaI of the original version of the Tutorial are listed in Appendix C.4 (p. 376).

Different Tutorials address the current–voltage relationship of individual circuit elements. The Tutorial *Current and Resistance* for example explicitly addresses that batteries are not current sources. The Tutorial *Voltage* also uses the fact that wires have no resistance. However, the IOaI of the Tutorial *Voltage* revealed that it never explicitly guided students to observe and compare the current–voltage characteristics of different circuit elements. Thus, students did not observe that batteries actually behaved as voltage sources or that wires have zero resistance.

The revised version of the Tutorial introduced three new tasks that are shown in Figure 8.19. Task 1.10 asks students to measure the voltage across a battery, a bulb, and a wire when the elements are connected to only a voltmeter. Task 1.11 then asks students to compare their different measurements of voltages across these three types of circuit elements. With this task, students can determine that batteries have a constant voltage across them, wires always have zero voltage drop, and that the voltage across a bulb changes depending on the circuit. Then, Task 1.12, which already was part of the Tutorial, asks students to determine the current–voltage relationship of bulbs and batteries. To reinforce batteries being voltage sources, task 1.13 asks students to investigate a battery to find that the voltage measured across it is also printed on the battery. This task can lead to some confusion as the capacity of a battery is often given in ampere hours, which students can confuse as a statement about the current of the battery.

To ensure the voltage measurements are correctly generalized and the battery capacity (given in ampere hours) is not misinterpreted, the prompt to discuss the answers with a TA (see bottom of Figure 8.19) was changed to specifically cover tasks 1.11 to 1.13.

8.3.1.3 *Removal of Voltage Across Open Switches*

The version of the Tutorial published in the *Tutorien zur Elektrotechnik* (Kautz, 2010) spanned 7 pages instead of the average length of a Tutorial of 4 pages. Most students were not able to finish the Tutorial during a typical recitation section. Therefore, the version of the Tutorial that was discussed above and used in the course EE1ME had been shortened by the removal of four sections (see Appendix B.4). As described above, the revised version re-introduced parts of these removed sections and introduced some new tasks. This change caused the Tutorial to become longer again.

In order to ensure that the Tutorial could be finished in time, the section *Voltage across open Switches* was in turn removed from the Tutorial. As discussed in Section 7.4, the voltage across an open switch is a difficult topic for many students and the Tutorial seemed not to improve students' answers on this concept. The voltage across an open switch was used as the metaphorical "hook" for the newly developed Tutorial on *Potential* (see Chapter 9).

8.4 SUMMARY

This chapter addressed RQ 2B using the Intended Observations and Inferences (IOaI) of Tutorials, i. e. the critical observations and inferences students are supposed to make when working through a Tutorial. These IOaI were uncovered in a collaborative process that had similarities to the first step of the DtD cycle labeled "uncover an expert's tacit knowledge".

RQ 2B: *Are there relevant conceptual difficulties that are not addressed by the existing Tutorial worksheets?*

Using this process, several conceptual difficulties were identified that had not addressed in the Tutorials. The Tutorial *Current and Resistance* showed an over-reliance on the concept of flow. Students likely were expected to understand KCL based on current being a flow. The Tutorial only addressed the two-wire case of KCL but contained no tasks that allowed students to observe KCL in the multi-wire case. A revision of the Tutorial was presented that included tasks for students to investigate both cases of KCL.

The importance of the role of the "interviewer" in determining the IOaI cannot be overstated. Without an interviewer who had no knowledge of electrical engineering, many "gaps" in the Tutorials would not have been recognized as such.

The revised Tutorial *Current and Resistance* was analyzed using post-tests. This investigation also revealed the misconception that KCL applies to the currents of circuit elements, not branches connected to the node. That misconception had not been described before and thus contributes to RQ 1B. The revision of the Tutorial *Voltage* was not tested explicitly. As the changes were considered more gradual in nature, testing the effect of these changes was considered less important than other investigations.

RQ 1B: *Are there conceptual difficulties with current and voltage in the electrical engineering curriculum that have not been identified before?*

8.5 OUTLOOK: GENETIC DECOMPOSITION OF TUTORIALS

This chapter described the revision of the Tutorials *Current and Resistance* and *Voltage* based on the IOaI that had been identified for both Tutorials. The revised Tutorials that were the result of this process are typical Tutorials. But, the IOaI of Tutorials can also be used for further revisions based on the APOS-Theory framework (see Section 2.5). Such a revision would likely result in drastic changes. This section describes how such a revision of the Tutorials might be carried out and what it could look like. Possible implications are also discussed.

Genetic decompositions are introduced in Section 2.5.3 (p. 42).

For a revision based on APOS-Theory, a genetic decomposition of the Tutorials is required. Such a genetic decomposition can be created based on the IOaI of the Tutorials. The IOaI can be transformed into a genetic decomposition quite easily. They already explicitly list all the concepts and relations students are supposed to learn. However, while the IOaI relate the individual concepts and relations to the tasks of the Tutorials, a genetic decomposition describes which concepts must be understood as an action, a process, and an object. It also describes which objects the individual actions and processes are performed on. In collaboration with the author of this thesis, Ed Dubinsky created a genetic decomposition based on the IOaI of the Tutorials *Current and Resistance* and *Voltage*. This decomposition can be found in Appendix D. It must be considered preliminary, since it is solely based on the understanding of the researchers involved in the creation of the decomposition and the IOaI of the Tutorials, and has not been verified through empirical means involving student data, as for example student interviews.

The first section of Appendix D describes the physical objects like wires and circuit elements that are subject of the Tutorials. These physical objects obviously have to be understood as objects. The second section (Appendix D.2) describes the concepts that describe the relation of the physical objects, for example series and parallel connections, as well as their electrical properties. Some of these elements are objects, some are processes. The last section (Appendix D.3) describes the properties of current, voltage, etc. These properties are actions applied to objects like current and voltage.

In the APOS framework, genetic decompositions are used to design appropriate instruction. Instruction is structured so that students acquire the necessary understanding of objects before they have to apply actions and processes to them. Such an object understanding is reached through an action and process understanding of the respective concepts.

Tutorials largely treat circuits as given and let students observe aspects such as the brightness of bulbs. From these observations students infer rules that describe the relations between current, voltage, and resistance. Compared to the existing Tutorials, instruction based on APOS-Theory involves more student activities that focus on performing actions. Such actions would be the physical and mental construction and manipulation of circuits or describing the path current takes through a circuit. While Tutorials contain some of these tasks, APOS-Theory posits that such tasks must be repeated many times to allow students to advance from an action to a process understanding. Such a revision of the Tutorials, however, was rejected for several reasons.

Firstly, APOS-style Tutorials could be unattractive to instructors. Revising the Tutorials based on APOS-Theory would result in substantive changes, especially to the beginning of the Tutorials. At the beginning of a course, instruction that is based on APOS-Theory often progresses more slowly than traditional instruction. Many new objects have to be constructed before students can use them to perform actions and processes. Dubinsky claims[12] that this slower start is often compensated or even overcompensated over the course of a whole semester. While the Tutorials are ideally used throughout a whole course, there are many courses that only use a few Tutorials for select topics. The course EE1ME (see Section 4.2.1) is such an example. APOS-style Tutorials would likely remove the possibility of such a use, as the first few Tutorials would be focused on the construction of very basic concepts, seemingly without progress. However, later Tutorials would build on and thus require the use of previous ones.

12 personal communication

Secondly, the high uncertainty of the outcome coupled with the sizable resources required for changes makes such an approach risky. APOS-Theory was developed for mathematics education and has rarely been used outside of that field. The Tutorials have been used successfully for decades. The benefit of changing Tutorials to conform with APOS-Theory is unclear, but would require a significant investment into the re-design and analysis of the Tutorials.

Thirdly, other approaches are available that are more in line with existing Tutorials. The previous chapter identified several conceptual difficulties students have. Most of these, like the voltage across an open switch, were addressed only partially or not at all in existing Tutorials. The creation of a new Tutorial following the established framework of conceptual change presented a more calculated risk compared to a rewrite of the existing Tutorials to accommodate for the APOS framework. The creation of this new Tutorial is described in the following chapter.

9 THE ELECTRIC POTENTIAL IN BASIC CIRCUIT ANALYSIS

Chapter 8 and especially Chapter 7 presented numerous student difficulties with the concept of voltage. This chapter discusses how the concept of the electric potential *is used* and how it *can be used* in engineering education to help students overcome some of these difficulties. It thereby helps to answer RQ 3:

RQ 3 To what extent can an improved understanding of the concept of electric potential help students overcome specific conceptual difficulties with voltage?

In particular, this chapter will focus on the effect of the electric potential on students' understanding of Kirchhoff's Voltage Law (KVL) and especially the voltage across open circuits, which can only be determined through KVL.

The chapter starts with a review of the electric potential and its use. Section 9.1 details the concept itself, while Section 9.2 gives an overview of where it can be encountered in engineering practice. Section 9.3 presents different uses of the electric potential in instruction through a survey of its use in different textbooks.

The remainder of the chapter analyzes the effect that an improved understanding of the electric potential can have on students' understanding of KVL. Section 9.4 presents different theoretical considerations. The section not only discusses the relation between the electric potential and different misconceptions identified in Chapter 7, but also compares the difficulty of circuit analysis using the electric potential and that using only KVL. Section 9.5 analyzes existing Tutorials which use the electric potential. A Tutorial used at Hamburg University of Technology[1] (TUHH) is analyzed, detailing why it was not as effective as could be expected based on the prior analysis in Section 9.4. Section 9.6 describes the development of a new Tutorial titled *Potential* and analyzes its effectiveness in respect to helping students overcome difficulties with KVL and in particular the voltage across open circuits. Section 9.7 summarizes and interprets relevant pieces of evidence discussed in this chapter.

9.1 THE ELECTRIC POTENTIAL

In DC circuit analysis, currents and voltages are time-independent, i. e. charges do move, but their spacial distribution is time-invariant.

1 "Technische Universität Hamburg" in German, formerly "Technische Universität Hamburg-Harburg".

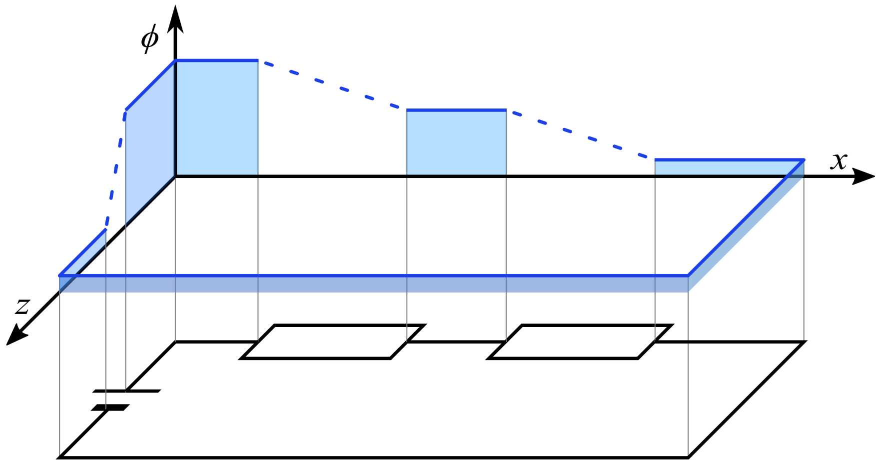


Figure 9.1: The scalar potential ϕ in a DC circuit. It is only defined for the wires of the circuit and marked by a solid blue line and light blue shading. The dashed line indicates a linear interpolation along the lengths of the circuit elements.

Magnetic fields do exist, but are constant over time. Thus, DC circuit analysis is part of magnetostatics and $\frac{\partial \mathbf{B}}{\partial t} = 0$ holds. Using this equation, Faraday's Law (Jackson, 1999, p. 211; Young and Freedman, 2004, p. 1216) can be simplified to

$$\operatorname{rot} \mathbf{E} = \nabla \times \mathbf{E} = 0, \qquad \text{or} \qquad \oint \mathbf{E}\, ds = 0. \tag{9.1}$$

Consequently, in magnetostatics, the electric field $\mathbf{E}$ is a conservative force field. As such, a scalar field ϕ can be used to describe it as

$$\mathbf{E} = -\operatorname{grad}(\phi) = -\nabla\phi, \qquad \text{or} \qquad \int_A^B \mathbf{E}\, ds = \phi_B - \phi_A. \tag{9.2}$$

This field ϕ is called the *electric potential* (Jackson, 1999, p. 29-31; Young and Freedman, 2004, pp. 880).

Equations 9.1 and 9.2 can be translated to the notation common in DC circuit analysis. Equation 9.1 becomes KVL, i. e. the voltages V_i in any closed loop sum up to zero:

$$\sum_i V_i = 0. \tag{9.3}$$

Equation 9.2 becomes the relation between the voltage from point A to point B and the electric potential at these points:

$$V_{AB} = \phi_A - \phi_B. \tag{9.4}$$

In the absence of time-dependent magnetic fields, the electric potential is defined as a scalar field with a value at every point in space. In DC circuit analysis, the electric potential is defined more narrowly.

Figure 9.1 shows the electric potential in a circuit diagram and illustrates three aspects: (1) As wires are considered ideal with $R = 0\,\Omega$, the voltage drop across them is $V = R \cdot I = 0\,V$. Thus, every point on a wire has the same potential. (2) As circuit diagrams do not represent physical dimensions, the potential is not defined in between the wires. (3) As the spacial dimensions of the symbols used in circuit diagrams have no relation to their function, the potential is not defined "on circuit elements". The symbol for the voltage source in Figure 9.1, for example, only states that there is a potential differences between the terminals of the source. It does not define the electric potential inside the source.

In the field of electrostatics and electrodynamics, the electric potential is usually denoted by ϕ (e. g. Jackson, 1999; Feynman et al., 1977). However, in the context of circuit analysis, the symbol for the electric potential is less standardized. Some textbooks use the symbol V for both voltage and the electric potential (e. g. Schwarz and Oldham, 1993, p. 22). To clearly differentiate between voltage and the electric potential, this text will always use ϕ for the electric potential and V for voltage.

9.2 USAGE IN ENGINEERING PRACTICE

Painting a complete picture of how the electric potential is *actually used* in electrical engineering practice is beyond the scope of this thesis. Still, it is useful to point out a few examples where the electric potential *is* or *could be* used in engineering practice.

9.2.1 *Usage in Standards*

To gain an overview of where the electric potential is used in engineering practice, standards can be analyzed. The International Electrotechnical Commission (IEC) publishes "standards for all electrical, electronic and related technologies" (IEC, 2019). It also publishes the International Electrotechnical Vocabulary (IEV), which lists all terms and definitions used in the IEC's standards. The IEV is published in printed form as the IEC 60050 series of standards and online as the *Electropedia* (IEC, 2019).

Overall, 1169 entries in the Electropedia contain 'voltage' as a single word and 1291 as part of a compound word[2]. 219 and 283 entries contain 'potential' as a single or part of a compound word, respectively. Thus, while 'voltage' is used about 5 times as often, 'potential' is still used regularly in the IEV.

Apart from general definitions that are similar to the one presented in Section 9.1 and uses in fields such as electrochemistry and electrobiology that are far removed from circuit analysis, the term 'potential'

2 Based on a search of "`voltage`" and "`*voltage*`".

is frequently encountered in the context of equipotential bonding (IEC, 2019). 'Equipotential bonding'[3] is defined in the IEV as the *provision of electric connections between conductive parts, intended to achieve equipotentiality* (IEC, 2019). It is for example used to prevent electric shock. When two conductive parts are on a different potential, a person touching both will have a voltage across their body. If the resulting current is too large, it can injure or even kill the person. A few other definitions in the Electropedia simply contain the term 'potential' in the general sense, such as *potential ignition source* in the context of risk management.

9.2.2 *Usage in Schematics*

The previous subsection analyzed where the electric potential occurred in standards in the field of electrotechnology by identifying definitions that contained the word. However, the electric potential can also be relevant without being named. One such example are schematics, especially schematics of DC circuits.

Figure 9.2 presents an excerpt of a schematic for a digital circuit. Schematics such as this one contain elements printed in red and their connections printed in green. The connections are often called *nets*, short for networks. Printed in gray are labels indicating the names of components, their pins, and nets. Some components or pins are directly connected by green wires to other components, as e. g. the three capacitors C4, C5, and C6 at bottom left, which are connected to the large integrated circuit, labeled IC3. Other components or pins are only connected by the name of their nets. Pin 98 on the integrated circuit IC3 for example is connected to the net AREF. Pin 3 of the connector JP6 in the bottom right of the schematic is also connected to the net AREF, meaning there is a connection between pin 3 on JP6 and pin 98 on IC3. The same is true for the net RESET, which connects pin 30 ($\overline{\text{RESET}}$) on IC3 with components at the top right of the schematic.

As all wires are considered ideal in such schematics, there is no voltage drop across them. There are no voltage arrows drawn between pins or wires in Figure 9.2. All voltages in the schematic are measured between the respective component and ground. Thus, effectively, each net is assigned a potential. As nets can be connected by their name and each net has one potential, the named nets effectively result in named potentials.

9.2.3 *Usage in Circuit Design*

Another field of electrical engineering that sometimes uses the electric potential without naming it as such is electronic circuit design. In their well known book on semiconductor circuit design, Tietze et al.

3 "Potentialausgleich" in German (IEC, 2019).

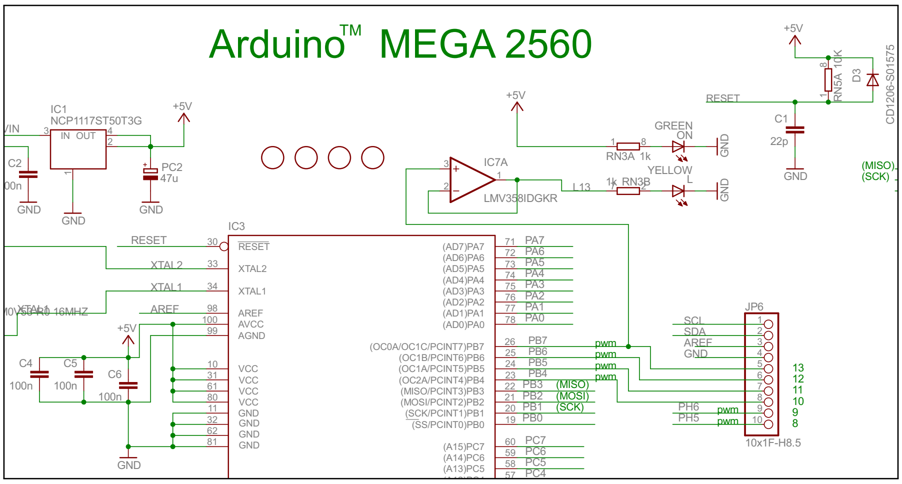


Figure 9.2: Excerpt of the schematic of the Arduino MEGA 2560, rev. 3 (Arduino AG, 2017). As can be seen, most of the nets (wires) are named. The nets RESET and AREF occur twice. Although they are not connected by a line, they are connected by their name. Schematic licensed as CC BY SA by Arduino AG.

(2016) comment on this practice when they define the electric potential:

> ***Potential*** The potential ϕ is the voltage of a node with relation to a common reference node 0:
>
> $$\phi_x = V_{x0}$$
>
> In electrical circuits, the reference potential is denoted by a ground symbol. Often V_x is used when actually implying ϕ_x. This is then, although not quite correctly, referred to as the voltage of a node, e. g. the collector voltage. The voltage between two nodes x and y then is:
>
> $$V_{xy} = \phi_x - \phi_y$$
>
> (translation of the German Tietze et al.[4], 2016, p. 1746)

An example for this practice can be found in Razavi (2010), a book on integrated circuit design. A circuit for a differential amplifier from that book is shown in Figure 9.3. The quantities V_{DD}, V_{in1}, V_{in2}, V_{out}, and V_b in that figure are referred to as voltages. They are meant to be measured between the point they are marked at and ground. However, while ground is shown in this circuit, it is only connected to M5, allowing for a current path from V_{DD} to ground. The voltages V_{DD}, V_{in1}, V_{in2}, V_{out} and V_b are not graphically related to ground, but "voltages of a node" as Tietze et al. (2016) would say. Consequently, it might make more sense to think of them as potentials instead of voltages.

4 In the English edition (Tietze et al., 2008), the quoted section is incomprehensible, as the symbol V is used for both voltage and potential.

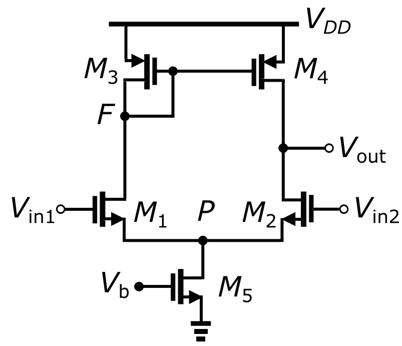


Figure 9.3: Differential amplifier as an example for a circuit in integrated circuit design. Reproduction of Figure 5.21a from "Design of Analog CMOS Integrated Circuits" by Razavi (2010). Reproduced with permission from McGraw Hill.

9.2.4 *Definition of Voltage*

As described in Section 9.1, 'voltage' is a *difference in electric potential between two points*. This definition can also be found in many dictionaries (Morris, 1981; Simpson et al., 1989; Duden, 2017).

However, as described by Tietze et al. (2016), voltage is sometimes used when actually implying a potential. This was for example observed in (Razavi, 2010). The Merriam-Webster dictionary lists both meanings, defining 'voltage' as *electric potential or potential difference expressed in volts* (Merriam-Webster, 2017). According to an editor of the dictionary[5], "this entry has been included in [the Merriam-Webster dictionary] with this or similar phrasing for at least 100 years. That means that the definition is based (at least partly) on evidence [of this usage of the word] that is at least that old."

9.3 THE ELECTRIC POTENTIAL IN TEXTBOOKS

The previous section presented different examples from engineering practice in which the electric potential was relevant. In some cases, the term 'potential' was stated explicitly, in others the electric potential was not mentioned at all. Similarly, there is a wide range of different approaches textbooks take on the usage and introduction of the electric potential. These can be split into three categories:

9.3.1 *No Usage of the Electric Potential*

Some authors, as e. g. Hambley (2008) do not use the term 'electric potential' at all even though they use the concept. Figure 9.4 shows a Figure from Hambley (2008), which is part of the introduction of the node voltage analysis. As can be seen, the author speaks of "voltages at [...] nodes" instead of potentials and uses a lower case v with an

5 Personal communication, 2017

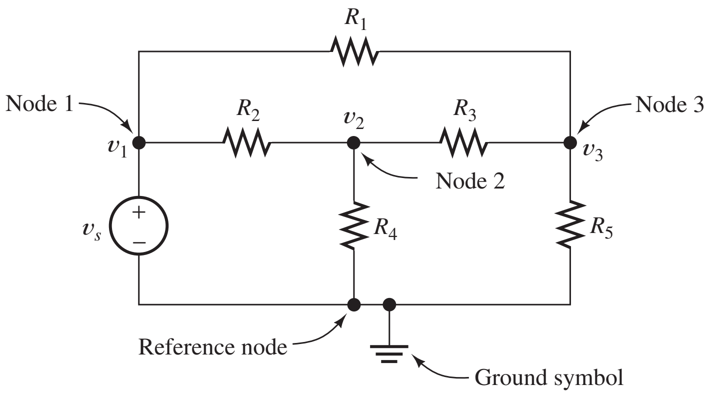


Figure 2.16 The first step in node analysis is to select a reference node and label the voltages at each of the other nodes.

Figure 9.4: Figure and caption from Hambley (2014) explaining the node voltage analysis. Reproduced with permission from Pearson Education, Inc., New York, New York.

index for these “voltages at [...] nodes” as well as the source voltage of the voltage source. Nilsson and Riedel (2005, p. 112) and Dorf and Svoboda (2011)[6] use a similar approach.

9.3.2 *Limited Introduction of the Electric Potential*

There are many textbooks that do introduce the electric potential, but only in a limited manner.

The textbook *Grundlagen der Elektrotechnik*[7] by Hagmann (2011) is widely used in Germany. Hagmann only mentions the electric potential when discussing *node voltage analysis*. There, he introduces the concept of electric potential at nodes. However, he continues by defining the term “node voltage” for the potential at a node. Thus, while he briefly mentions the electric potential, his book does not use the concept in DC circuit analysis. The electric potential is then only used again in the context of electric fields. Hagmann confirmed that this limited use of the electric potential was intentional:

> “In my opinion, it is not problematic to introduce the electric voltage in DC circuits without the ‘detour’ of the electric potential. This approach is, in my opinion, not only shorter, but also clearer for the introduction of freshmen to electrical engineering.”[8]

6 Dorf and Svoboda (2011) mention the electric potential twice: Once when defining symbols and once in a task on three-phase current.

7 German for “Fundamentals of Electrical Engineering”.

8 Personal communication, Feb. 28th, 2017. German original: “In der Gleichstromtechnik kann die Einführung der elektrischen Spannung meiner Meinung nach problemlos ohne den ‘Umweg’ über das elektrische Potenzial vorgenommen werden. Zudem ist dieser Weg für Studienanfänger, die in das Gebiet der Elektrotechnik eingeführt werden, meiner Meinung nach nicht nur kürzer, sondern auch verständlicher.”

Similarly, Warnes (1994) also only mentions the potential in the context of the *node voltage analysis* while never formally introducing the concept.

Bird (2010) mentions *potential difference* (e. g. pp. 10 and 37) and even uses the name "potential divider" for the voltage divider (p. 37). However, when introducing the node voltage analysis, he does not mention the electric potential at all, but instead speaks of node voltages:

> "A node voltage is the voltage of a particular node with respect to a node called the reference node."
>
> (Bird, 2010, p. 429)

9.3.3 *Explanation of KVL Through the Electric Potential*

Several authors introduce the electric potential as a distinct quantity besides voltage. As such, it can be used to explain or even "prove" KVL.

After introducing the concept of voltage, Ameling (1988) for example states that "It has proved useful to introduce the *electric potential* ϕ in addition to the voltage V"[9] (p. 25). He then uses the electric potential in the equation

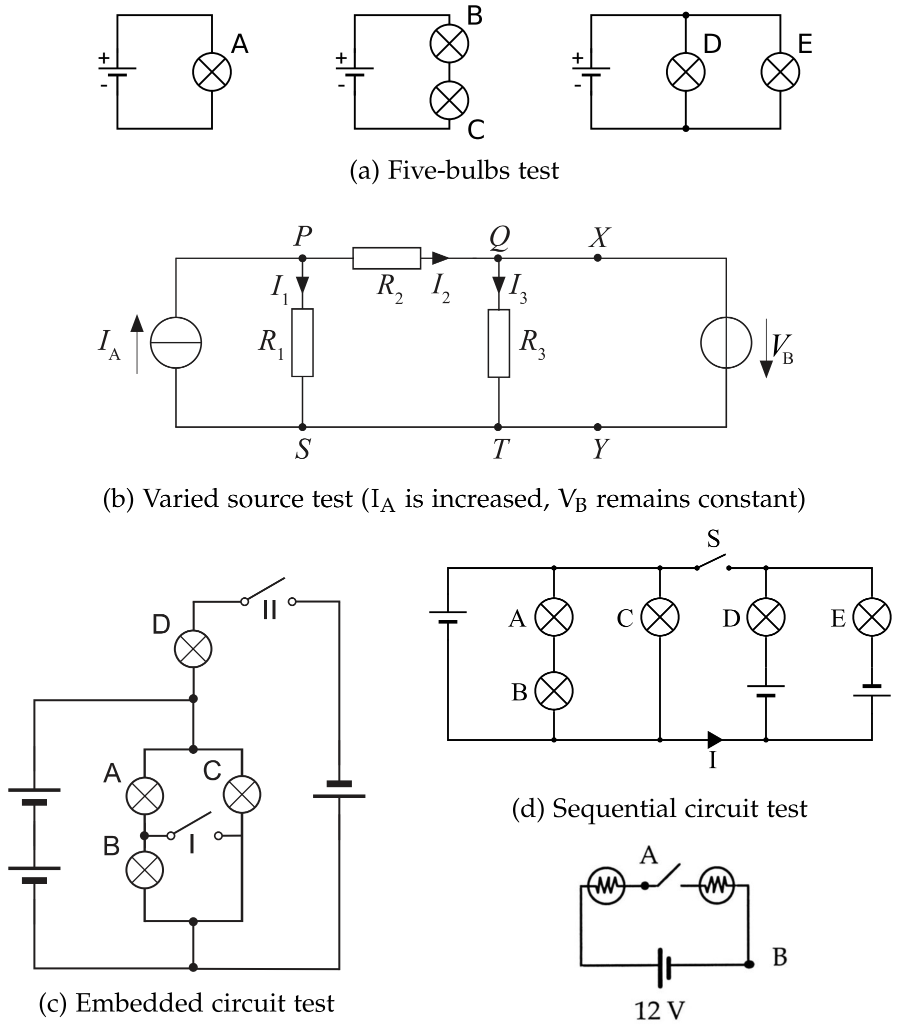
$$V_{12} + V_{23} + V_{31} = (\phi_1 - \phi_2) + (\phi_2 - \phi_3) + (\phi_3 - \phi_1) = 0.$$

to introduce and explain KVL (Ameling, 1988, p. 29).

Young and Freedman (2004) similarly argue that "the loop rule is a statement that the electrostatic force is conservative. Suppose we go around a loop, measuring potential differences across successive circuit elements as we go. When we return to the starting point, we must find that the *algebraic sum* of these differences is zero; otherwise, we could not say that the potential at this point has a definite value" (p. 987, emphasis theirs). Schwarz and Oldham (1993, pp. 22, 32-33) use the same approach, also explaining KVL using the electric potential.

9.4 BENEFITS OF UNDERSTANDING AND USING THE ELECTRIC POTENTIAL

The previous section gave an overview of different ways the electric potential is presented to students. This section will detail ways in which the understanding of the electric potential can help students.



(a) Five-bulbs test

(b) Varied source test (I_A is increased, V_B remains constant)

(c) Embedded circuit test

(d) Sequential circuit test

(e) Circuit from the DIRECT

Figure 9.5: Overview of different circuits used in Chapter 7 in which students failed to correctly apply KVL.

9.4.1 *Student Difficulties Using KVL*

Several tests presented in Chapter 7 investigated students' understanding of KVL. It was found that in many cases, students were not able to correctly apply KVL in qualitative settings. Some of the circuits used for this investigation are shown in Figure 9.5.

Section 7.1.4 (p. 116) discussed the five-bulbs test (circuit shown in Figure 9.5a) where 32% to 67% of students failed to recognize that bulbs D and E were as bright as bulb A, i. e. that the voltage across them was the same. As discussed in Section 7.1.5 (p. 118), this difficulty even occurred when ideal voltage sources were used instead of batteries. Section 7.2.1 (p. 120) presented a test using a varied

9 German original: "Es hat sich als zweckmäßig erwiesen, neben der Spannung U noch das *elektrische Potential* ϕ einzuführen." (Ameling, 1988, p. 25)

source (circuit shown in Figure 9.5b) in which 49% of students failed to recognize that the voltage across R_3 was held constant by V_B even when the source current I_A was increased. Several tests analyzed in Section 7.2.2 (p. 123) used a circuit consisting of two parts, an outer one and an embedded inner one (circuit shown in Figure 9.5c). In this circuit, 73% to 75% of students failed to recognize that bulb C stayed equally bright when switch II was closed, i. e. that the voltage across bulb C was not affected by the switch. Two different tests discussed in Section 7.2.3 (p. 125) used a sequential circuit (shown in Figure 9.5d), in which 41% to 54% of students failed to determine that bulb C stayed equally bright when switch S was closed, i. e. that the voltage across it was not affected by the switch. In addition, Section 7.4 (p. 133) presented a large study of four different tests with open circuits and open switches. 52% of 5607 students falsely believed the voltage across the open circuits and switches in these tests was zero. The circuit of one of these tests is shown in Figure 9.5e.

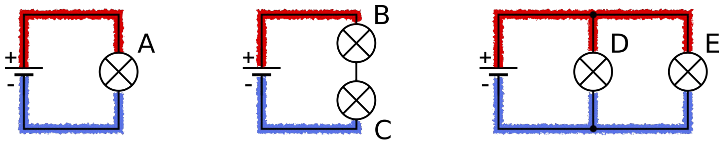
To correctly answer the questions discussed above, students had to find a loop containing only the element in question (bulb, resistor, or open switch) and one or more sources (batteries or voltage sources). Using KVL they could then find the voltage across the element in question to be determined by the voltage across the source(s). In the questions regarding the open circuit (e. g. Figure 9.5e), students had to additionally use the fact that no voltage drops across the bulbs in series with the open switch.

As shown in Section 7.2.3 (p. 125) students were more likely to correctly answer these questions when the element in question was closer to the source(s), i. e. the loop was smaller. As shown in Section 7.2.2 (p. 123) incorrect answers tended to focus on the current through the element in question, assuming a certain path of the current. Students' difficulties could have been aggravated by a flawed understanding of sources (see Section 7.3, p. 127). However, the frequent difficulties with voltages across open circuits indicate that a key difficulty indeed is the application of KVL.

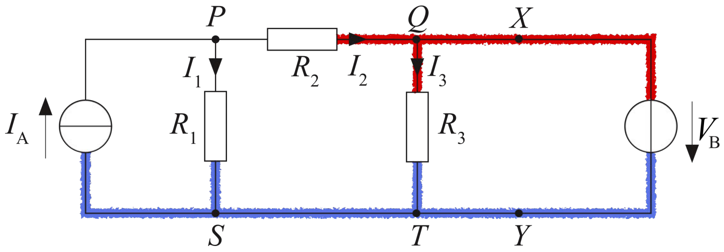
9.4.2 *Suggested Use of the Electric Potential in Instruction*

Introducing students to the electric potential could help them overcome the difficulties presented in the previous section. Specifically, three benefits can be distinguished:

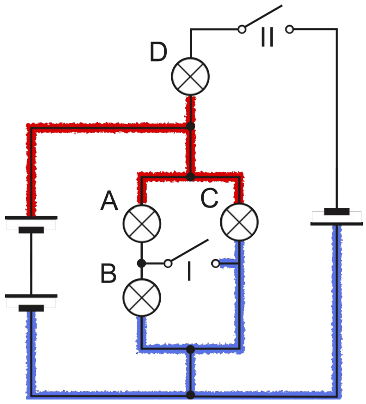
Firstly, the electric potential provides an alternative method to KVL for answering some problems in circuit analysis. Figure 9.6 shows the same circuits as Figure 9.5, this time with regions that have the potential of the upper and lower terminal of the relevant source(s) coded in red and blue, respectively. In each circuit, the element in question is attached to these two regions. As the difference between the two potentials is fixed by the source(s), the potential difference,



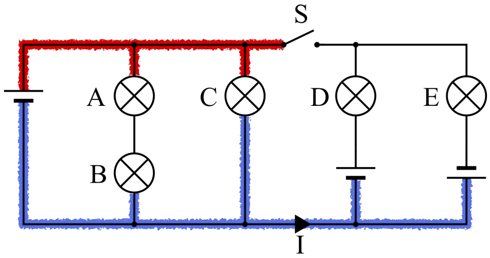
(a) Five-bulbs test



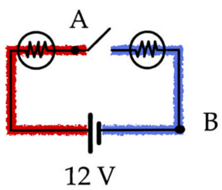
(b) Varied source test (I_A is increased, V_B remains constant)



(c) Embedded circuit test



(d) Sequential circuit test



(e) Circuit from the DIRECT

Figure 9.6: Circuits from Figure 9.5 with color-coding to mark the areas with the same potential as the positive and negative lead(s) of relevant sources that determine the voltage across (a) all bulbs, (b) R_3, (c and d) bulb C, and (e) the open switch. In the tests given to students (see Appendix E), no color-coding was used.

i. e. voltage, across the element in question is also fixed. In circuits like these, the electric potential can be used instead of KVL to determine the correct answer. Alternatively, the potential can be used in these circuits to verify results determined through KVL.

Secondly, KVL can either be explained by the electric field being a conservative force field or by using the electric potential, as was shown in Section 9.3.3. It is likely that it is easier for students to understand what a potential is, especially by referring to other potentials they already know, than to understand conservative forces on their own. This assumption is supported by the analysis that will be shown in Section 9.4.4.

Thirdly, the color-coding based on the electric potential that is presented in Figure 9.6 could help to combat local reasoning, which was discussed on pages 115 and 170. When using KVL, students have to use closed loops in the circuit under investigation that – by nature – lead back to their start, often the source. To reduce the complexity of the KVL equations, these loops should be as small as possible. It is likely that focusing on loops that always return to the source and are as short as possible conduces local reasoning, where students do not see the effects of elements like sources on other elements at the other end of the circuit. In contrast, the color coding shown in Figure 9.6 highlights the connections of elements, even when they are far apart.

9.4.3 *Voltage–Potential Confusion*

As reported on page 113 in Section 7.1.3, some students failed to distinguish between voltage and potential. They believed that the potential at one terminal of a bulb (usually the upper one) indicated its brightness instead of the potential difference across it. When investigated by McDermott and Shaffer (1992), this failure was observed about as often as the belief that current is "used up". This prevalent failure might be seen as an argument to not introduce students to the electric potential. After all, if they do not know the electric potential, one might argue that they cannot incorrectly use it instead of voltage.

Contrary to this assumption, students in courses that do not use the electric potential also make this failure in their answers, albeit without explicitly using the term 'potential'. This surprising observation was reported on page 113 in Chapter 7 when analyzing student answers to the five-bulbs test in the course EE1ME.

As detailed in Section 9.4.2, introducing students to the electric potential likely has several benefits. As discussed above, not introducing them to the electric potential does not prevent them from confusing it with voltage.

9.4.4 *Comparison of Circuit Analysis Using Voltage and Potential*[10]

The previous sections reviewed student difficulties with KVL and described why introducing them to the electric potential might be beneficial. This section tries to visualize how demanding circuit analysis based on KVL is for novices, simply due to the complexity of the considerations that have to be made. The complexity of circuit analysis using KVL is compared to that of circuit analysis using the electric potential.

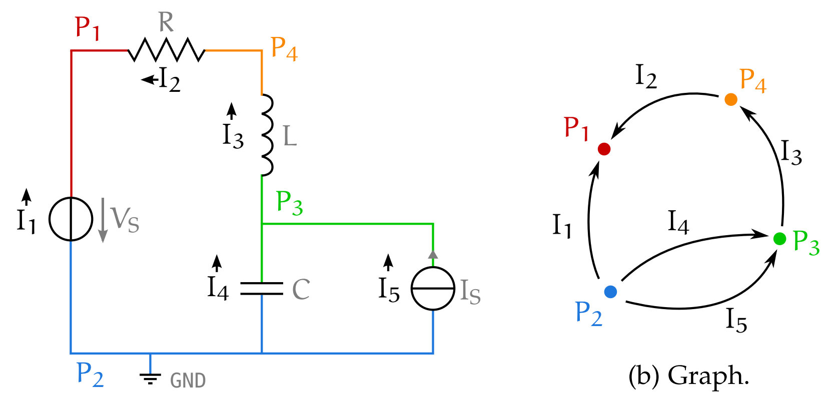
For experts, who have practiced electrical engineering for years, it can be almost impossible to objectively assess the difficulties associ-

10 The mathematical descriptions discussed in this section were created in collaboration with Ed Dubinsky.

ated with circuit analysis. They likely have become so accustomed to circuit analysis that they do not even have to consciously think about many of its steps. In addition, Middendorf and Pace (2004) note that "faculty generally chose to go into fields where they were successful [...]. Therefore, they may have leaped almost automatically over obstacles that can prove daunting to novices" (p. 5). In order to understand student difficulties, they suggest experts "distance themselves from all that is natural and automatic to members of their field" (p. 5).

In this section, two mathematical descriptions of circuit analysis will be used to show the considerations necessary in circuit analysis. One description will be based on circuit analysis using the electric potential, the other on circuit analysis using KVL. Both descriptions represent the relations between the currents and voltages in networks consisting of resistors, inductors, capacitors, ideal current sources, and ideal voltage sources. Thereby, they allow to mathematically "solve" circuits by determining all voltages, currents, and impedances.

The mathematical descriptions will be illustrated using the circuit whose circuit diagram is shown in Figure 9.7a. While circuit diagrams are usually drawn in black ink, colors were added here to highlight regions of equal potential (P_1, P_2, P_3, and P_4). The circuit contains all five types of typical circuit elements: a resistor (denoted by an R), an inductor (L), a capacitor (C), a voltage source (marked with the source voltage V_S), and a current source (marked with the source current I_S). The GND symbol defines potential $P_2 = 0\,V$. The arrows marked I_1 through I_5 are usually not drawn in a circuit diagram. They are displayed here to give each circuit element a number and define the direction in which the current through the element is counted.



(a) Circuit diagram.

(b) Graph.

Figure 9.7: Circuit diagram and corresponding graph representation of a circuit.

9.4.4.1 *Graph Representation*

Both mathematical descriptions rely on a graph representation of the circuit that contains the information about the topology of the circuit. The graph of the example circuit is shown in Figure 9.7b. Regions of equal potential are collapsed to nodes. These nodes are connected by arcs, each representing one circuit element. The direction of the arc is the same as the direction in which the current through this element is counted in the circuit diagram (Figure 9.7a). The types of the individual circuit elements cannot be seen in the graph, but will be encoded in the mathematical descriptions.

9.4.4.2 *Mathematical Description of a Circuit with the Electric Potential*

While the graph contains all information about the topology of the circuit, i. e. which circuit elements exist and how they are connected, it does not contain information about the types of circuit elements or their values. This information is part of the mathematical description of the circuit. The mathematical description using the electric potential is presented in Figure 9.8 and explained in the remainder of this subsection.

The mathematical description in Figure 9.8 starts with the definition of an 8-tuple that defines the electric circuit. The elements of the 8-tuple are explained and further specified by the list of items 1. to 6.:

1. $(\mathcal{P}, \mathcal{I})$ describes the first element of the 8-tuple, the graph that represents the topology of the circuit. The graph is written as the set $\mathcal{P}$ containing all the nodes and the set $\mathcal{I}$ containing the directed arcs between pairs of nodes. As noted earlier, this graph only names each node (representing a wire) and the connecting arcs (representing circuit elements), but does not contain information about their types.

2. The types of circuit elements are defined through the three sets $\mathcal{I}_Z$, $\mathcal{I}_C$, and $\mathcal{I}_V$. Each arc (circuit element) is part of one of these sets. Impedances are part of the set $\mathcal{I}_Z$, current sources part of $\mathcal{I}_C$ and voltage sources part of $\mathcal{I}_V$. The values of the impedances as well as the source voltages and source currents are defined as part of the functions c, z, and v below.

3. The function p assigns the potential $p(P)$ to each node P in the graph, i. e. each wire in the circuit. The values of the respective potentials, i. e. the values $p(P)$, are later constricted through equations (2) and (3). If a circuit had a defined potential, e. g. if a ground symbol were used, the respective value $p(\mathcal{P})$ would be defined by the circuit. The ground symbol in Figure 9.7a for example is equivalent to $p(P_2) = 0\,V$.

4. The function v assigns the voltage $v(I)$ to each arc I (i.e. circuit element) in the graph. Equation (3) defines the voltages as potential differences.[11] The source voltages of voltage sources are equal to the voltage across the source. Thus, for voltage sources $v(I)$ is (equal to) the source voltage.

5. The function i assigns the current $i(I)$ to each arc I (i.e. circuit element) in the graph. Equation (1) describes the relations of the individual currents. The source currents of current sources are equal to the current through the source. Thus, for current sources $i(I)$ is (equal to) the source current.

6. The function z assigns the impedance $z(I)$ to each arc I (i.e. circuit element) that is an impedance (i.e. $I \in \mathcal{I}_Z$). For most circuit problems, the values of impedances are known. In these cases the values $z(I)$ are defined for the respective circuit elements. In AC circuit analysis, the different impedances are determined by their value on the complex plane. Resistances have a value of $z = R$, inductances have a value of $z = i\omega L$, and capacitances have a value of $z = -i \cdot {}^1/_{\omega C}$ with $R, L, C, \omega \in \mathbb{R}$ and $R, L, C, \omega > 0$.

The text below item 6 defines $\mathcal{I}_{P+}$, a shorthand for all the arcs (i.e. circuit elements) whose current flows out of node P, and $\mathcal{I}_{P-}$, a shorthand for all the arcs (i.e. circuit elements) whose current flows into node P. Also, $\mathcal{P}_{I+}$, a shorthand for the node the current I flows out of and $\mathcal{P}_{I-}$, a shorthand for the node the current I flows into, is defined.

Using these definitions in Figure 9.8, Kirchhoff's Current Law and Ohm's Law can be written as equations (1) and (2) (see Figure 9.8). As described above, the voltages are defined based on the potential using equation (3) (see Figure 9.8).

9.4.4.3 *Mathematical Description of a Circuit without the Electric Potential*

The mathematical description discussed above did not contain KVL, but instead used the electric potential to define voltages. When KVL is to be used, some modifications to the description are necessary, resulting in the mathematical description shown in Figure 9.9. The differences between the two mathematical descriptions are highlighted in red. As can be seen, the two mathematical descriptions are mostly identical. The changes can be attributed to two aspects:

First, the electric potential is removed from the definition, reducing the 8-tuple to a 7-tuple and resulting in the elimination of equation (3) in Figure 9.8.

11 This mathematical description only defines the voltages across circuit elements, but not between any pair of nodes in a circuit. If that were required, the definition could be modified to $v : \mathcal{P} \times \mathcal{P} \to \mathbb{C}$ with $v(P_b, P_a) = p(P_b) - p(P_a)\ \forall\ P_a \in \mathcal{P}, P_b \in \mathcal{P}$.

An *electric circuit* E is defined to be a 8-tuple $E = ((\mathcal{P}, \mathcal{I}), \mathcal{I}_Z, \mathcal{I}_C, \mathcal{I}_V, p, c, z, v)$ where:

1. $(\mathcal{P}, \mathcal{I})$, is a graph with set of nodes $\mathcal{P}$ and set of directed arcs $\mathcal{I}$;
2. $(\mathcal{I}_Z, \mathcal{I}_C, \mathcal{I}_V)$ are sets that form a pairwise disjoint decomposition of the set $\mathcal{I}$.
3. $p : \mathcal{P} \to \mathbb{C}$ is a complex-valued function on $\mathcal{P}$. It is called *potential*.
4. $v : \mathcal{I} \to \mathbb{C}$ is a complex-valued function on $\mathcal{I}$. It is called *voltage*. For arcs in $\mathcal{I}_V$, it is also called *source voltage*.
5. $c : \mathcal{I} \to \mathbb{C}$ is a complex-valued function on $\mathcal{I}$. It is called *current*. For arcs in $\mathcal{I}_C$, it is also called *source current*.
6. $z : \mathcal{I}_Z \to \mathbb{C}$ is a complex-valued function on $\mathcal{I}_Z$ such that $\forall I \in \mathcal{I}_Z, \mathrm{Re}(z(I)) \leqslant 0$. It is called *impedance*;

For each $P \in \mathcal{P}$, $\mathcal{I}_{P+}(\mathcal{I}_{P-})$ is the set of arcs in $\mathcal{I}$ whose tail (head) is P. For each I in $\mathcal{I}_{P+}$, P_{I+} is the tail of the arc I and P_{I-} is the head of the arc I.
Moreover, the following relations hold:

$$\forall P \in \mathcal{P}, \quad \sum_{I \in \mathcal{I}_{P+}} c(I) = \sum_{I \in \mathcal{I}_{P-}} c(I) \tag{1}$$

$$\forall I \in \mathcal{I}_Z, \quad z(I) \cdot c(I) = v(I) \tag{2}$$

$$\forall I \in \mathcal{I}, \quad p(P_{I+}) - p(P_{I-}) = v(I) \tag{3}$$

Figure 9.8: Abstract definition of circuits using the electric potential. Differences to the version not using the potential (Figure 9.9) are printed in red font.

Second, a mathematical definition for a closed loop is added above the equation. Such a loop is a sequence of nodes (Q_i) and arcs (K_i). Through the order of its elements, this loop has a direction. For each element in the loop, the direction of the arc and the direction of the loop are compared and ϵ_i is defined as $+1$ if both directions are the same or -1 if they are not. Then, KVL is added as equation (3) in Figure 9.9.

9.4.4.4 *Comparison of the Mathematical Descriptions*

While both descriptions have largely the same structure and many identical elements, there are some differences. The description using the electric potential has an additional quantity: the electric potential.

An *electric circuit* E is defined to be a 7-tuple $E = ((\mathcal{P}, \mathcal{I}), \mathcal{I}_Z, \mathcal{I}_C, \mathcal{I}_V, c, z, v)$ where:

1. $(\mathcal{P}, \mathcal{I})$, is a graph with set of nodes $\mathcal{P}$ and set of directed arcs $\mathcal{I}$;

2. $(\mathcal{I}_Z, \mathcal{I}_C, \mathcal{I}_V)$ are sets that form a pairwise disjoint decomposition of the set $\mathcal{I}$.

3. $v : \mathcal{I} \to \mathbb{C}$ is a complex-valued function on $\mathcal{I}$. It is called *voltage*. For arcs in $\mathcal{I}_V$, it is also called *source voltage*.

4. $c : \mathcal{I} \to \mathbb{C}$ is a complex-valued function on $\mathcal{I}$. It is called *current*. For arcs in $\mathcal{I}_C$, it is also called *source current*.

5. $z : \mathcal{I}_Z \to \mathbb{C}$ is a complex-valued function on $\mathcal{I}_Z$ such that $\forall I \in \mathcal{I}_Z, \mathrm{Re}(z(I)) \leqslant 0$. It is called *impedance*;

For each $P \in \mathcal{P}$, $\mathcal{I}_{P+}(\mathcal{I}_{P-})$ is the set of arcs in $\mathcal{I}$ whose tail (head) is P. For each I in $\mathcal{I}_{P+}$, P_{I+} is the tail of the arc I and P_{I-} is the head of the arc I.
A closed loop in an electric circuit is a sequence $(Q_i, K_i)_{i=1}^n$ where each Q_i is a node in the circuit; no Q_i appears twice in the sequence; and each K_i is an arc in the circuit such that, for each $i = 1, 2, \ldots, n-1$, either Q_i is the tail of K_i and Q_{i+1} is the head of K_i, or Q_i is the head of K_i and Q_{i+1} is the tail of K_i and either Q_n is the tail of K_n and Q_1 is the head of K_n, or Q_n is the head of K_n and Q_1 is the tail of K_n. For any closed loop, $(Q_i, K_i)_{i=1}^n$, in a circuit, we define the sequence $(\epsilon_i)_{i=1}^n$ as follows. For $i = 1, 2, \ldots, n$, if Q_i is the tail of K_i, then $\epsilon_i = 1$ and if Q_i is the head of K_i, then $\epsilon_i = -1$.
Moreover, the following relations hold:

$$\forall P \in \mathcal{P}, \sum_{I \in \mathcal{I}_{P+}} c(I) = \sum_{I \in \mathcal{I}_{P-}} c(I) \qquad (1)$$

$$\forall I \in \mathcal{I}_Z, \quad z(I) \cdot c(I) = v(I) \qquad (2)$$

$$\text{For any closed loop,} (Q_i, K_i)_{i=1}^n, \text{in a circuit,} \sum_{i=1}^{n} \epsilon_i \, v(K_i) = 0 \qquad (3)$$

Figure 9.9: Abstract definition of circuits *not* using the electric potential. Differences to the version using the potential (Figure 9.8) are printed in red font.

The description using KVL on the other hand contains a description of what a closed loop is. The third equation differs between the two versions. In one version, the voltage is related to the potentials, in the other the voltages are related through KVL.

The mathematical description shown in Figure 9.8 uses both, the potential p and the voltage ν. As voltages are simply potential differences, they could technically have been removed, reducing the description to a 7-tuple. However, voltages are commonly used in electrical engineering. Without voltages, the description would be far removed from the way circuits are usually described. Voltages are used frequently and thus should be part of the description.

Based on the length of text, the largest difference between the two versions is the addition of the definition for a closed loop in the description without the electric potential. The description presented here must be considered one of many possible descriptions. It is likely that a shorter description of a closed loop can be written. Nevertheless, such a description needs to define (1) what a closed loop is, (2) the direction of the loop, and (3) the summation of the voltages in the loop based on the direction in which they are counted in the graph and the direction of the loop. While that may seem trivial to an expert, the mathematical description reveals the number of steps required and highlights that 'closed loop' might be a concept that is easy once understood, but difficult to communicate.

The large number of steps for finding a loop and applying KVL to it as well as the difficulty in describing what a closed loop is might be a key factor in students' difficulties with KVL.

9.4.5 *Conclusion*

Sections 9.4.1 and 9.4.3 presented multiple pieces of evidence where students failed to correctly apply KVL. Section 9.4.2 argued why the electric potential might help students overcome these difficulties. Section 9.4.4 showed the complexity of KVL using mathematical descriptions. The mathematical descriptions show that the electric potential is easier to describe and thus likely also easier to understand. It can be used as an alternative to voltage in some circuit problems. It likely provides an easier explanation for KVL than the concept of conservative force fields and it could also help to address local reasoning.

Still, the concept of voltage is central to electrical engineering. The electric potential must only supplement the concept of voltage and cannot replace it.

The two subsequent sections will explore different qualitative worksheets that try to employ the benefits of the electric potential described above.

9.5 EXISTING QUALITATIVE WORKSHEETS USING THE ELECTRIC POTENTIAL

As described in the previous section, there are good reasons why the electric potential might be a useful tool to help students better understand KVL. It is therefore relevant to investigate if and how the electric potential is used in existing Tutorials. Some other Tutorials, developed by other researchers, do use the electric potential. In the following, an overview of some of these will be given and their success will be evaluated.

9.5.1 *Usage of the Electric Potential in the Tutorials in Introductory Physics*

The English *Tutorials in Introductory Physics* (McDermott and Shaffer, 2002) contain two Tutorials that mention the electric potential: The Tutorial *Electric potential difference* (pp. 85-90) and *A model for circuits part 2: Potential difference* (pp. 103-106). However, both Tutorials only use 'potential' in the context of potential difference. In these Tutorials, the phrase 'potential difference' could be replaced by 'voltage'. The potential *at a point* is never used.

9.5.2 *Tutorial "Voltage" by Kautz*

The Tutorial is described in Appendix B.6 (p. 351)

The published version of the Tutorial *Voltage* in the German *Tutorials in Electrical Engineering* (Tutorien zur Elektrotechnik, Kautz, 2010) is a translation and extension of the aforementioned *A model for circuits part 2: Potential difference*. In the Tutorial *Voltage* the phrase 'potential difference' was replaced with 'voltage'. In addition, a section introducing the electric potential was added. The Tutorial is 7 pages long and the electric potential is only introduced on page 6. Informal classroom observations show that students usually are able to work through 3 to 4 pages of a Tutorial during a regular 90 minute recitation section. Thus, it is likely that the section on the electric potential was only reached by few students.

9.5.3 *Tutorial on Multiple Batteries by Smith and van Kampen*

Smith and van Kampen (2011) reported on their research on student understanding of circuits with multiple batteries. They developed several Tutorials. One introduced students to the concept of the electric potential, another used the electric potential to help students understand circuits with multiple batteries. Smith and van Kampen (2011) report: "The introduction of the concept of potential allowed students to systematically discover rules for how circuits with multiple batteries in multiple loops can be modeled. Post-test results show that the majority of students were able to apply their newly developed model to make accurate predictions for complex circuits. The analysis of their answers also revealed an increased understanding of the roles current, voltage, and resistance play in their model for electric circuits. However, students still found it difficult to transfer their understanding to a new context."

While they reported to have successfully used the electric potential to help students understand circuits with multiple batteries, their Tutorials were designed to be used in the tutorial series *Physics by Inquiry* (McDermott et al., 1996). That series is designed for a course that almost exclusively uses Tutorials instead of traditional instruction. Their Tutorials had a much slower pace than what was required for the course EE1ME. They also had not addressed KVL in general or open circuit voltages specifically in their Tutorials.

9.5.4 *Custom Version of the Tutorial "Basic Circuit Analysis"*

The full Tutorial "Basic Circuit Analysis" is presented in Appendix B.7 (p. 351).

As reported in Section 7.2 (p. 120), students who had worked through the Tutorials *Current and Resistance* and *Voltage* in the course EE1ME, failed to correctly apply KVL in simple cases, such as a circuit element in parallel to a voltage source or battery. To improve students' understanding of KVL, a new Tutorial was introduced in the course. This Tutorial was used after students had worked through the Tutorial *Voltage* (see Appendix A). It spans 4 pages and is a combination of tasks that were removed from the Tutorial *Voltage* due to its length as well as tasks from the Tutorial *Basic Circuit Analysis*, which was not used in that course. The Tutorial is described and analyzed in the remainder of this section.

9.5.4.1 *Section 1: Revision*

The Tutorial starts with a discussion of the concepts of parallel and series connection. Like in the Tutorial *Phase Relations* (Kautz, 2010, pp. 97-100), students are asked to define series and parallel connections without using the terms current and voltage. Students are then asked about the relations of the current through and the voltage across two circuit elements that are connected in series or in parallel. This sequence of tasks is used to help students recognize that series and parallel connections are not consequences of circuit elements having the same current or voltage, but that instead series and parallel connections are aspects of the circuit's topology, which in turn results in these elements having the same current or voltage.

The Tutorial then reviews the relation between a bulb's brightness, the current through the bulb, and the voltage across it. This is a repetition of the key results of the Tutorials *Current and Resistance* and *Voltage* described in Chapter 8.

All these tasks use the circuit shown in Figure 9.10.

2 Investigation of circuits using the electrical potential

In order to determine the voltage between two distant points in a circuit more easily, we introduce the term *electric potential*. The potential *difference* between two arbitrary points within a circuit is equal to the voltage between those two points. (e. g. $V_{PQ} = \Phi_P - \Phi_Q$).

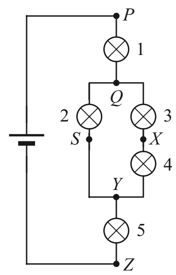
The potential Φ at *any arbitrary* point is then defined by assigning an arbitrary value to a certain point within the circuit. Often, the negative terminal of a battery is assigned a potential of $\Phi = 0\,\mathrm{V}$. Then, the positive terminal of that battery has the potential $\Phi = V_{\mathrm{Batt}}$.

2.1 *Potentials in a circuit*

The circuit from Part 1 is repeated at right.

a. Order points P, Q, S, X, Y, and Z by their electric potential. Explain.

b. Did you find points that have the same potential? If so, how did you finde these? If not, why are there none?



c. To illustrate the different values of the potential in the circuit diagram, color coding can be used. Mark *all* points of equal potential (i. e. an entire area of the circuit) with the same color (e. g. red for the highest potential, blue for the lowest, etc.).

d. Describe, how you identified points of equal potential.

e. How can you use the color coding to identify circuit elements or groups of circuit elements that are connected in parallel?

2.2 *Potential and Voltage*

a. Is it possible that the potential difference across two circuit elements is equal while all terminals have different potentials? If so, try to give an example based on the circuit above. If not, explain why not.

b. Is it possible for two circuit elements to have the same potential at the terminal with higher potential, but different voltages across the elements? If so, try to give an example based on the circuit above. If not, explain why not.

Figure 9.10: Page 2, custom version of the Tutorial *Basic Circuit Analysis*.

9.5.4.2 *Section 2: Electric Potential*

In Section 2, the Tutorial introduces the concept of the electric potential (see top of Figure 9.10) as a method or tool "to determine the voltage between to distant points in a circuit more easily". The definition is quite formal. Instead of defining the electric potential directly, the "potential *difference*" is defined to be the same as voltage. The equation $V_{PQ} = \phi_P - \phi_Q$ is used as an example. The variable ϕ for the potential is only defined afterwards, also discussing the arbitrary offset of the electric potential. A second short example for the electric potential is given when the convention of using the potential 0 V for the negative terminal of a battery is stated.

The first task using the electric potential (task 2.1.a) immediately asks students to rank six points in the circuit by their potential and describe their approach to determine these potentials (task 2.1.b). These two tasks are designed so that students must recognize $S = Y$ and $X \neq S$, i. e. that the vertical position in the circuit is not relevant for the electric potential. However, as electric potential was introduced based on voltages, it is likely that students base their answer on their understanding of voltage.

Then, the Tutorial introduces color coding (tasks 2.1.c and 2.1.d) and highlights a use of this method (task 2.1.e). Color coding can be used to visualize the topology of a circuit and thus determine how its components are connected.

Section 2.2 of the Tutorial (bottom of Figure 9.10) examines the differences between voltage and potential. Task 2.2.a asks students to find that different potentials do not necessarily result in different voltages, as voltages are *potential differences* and not directly related to the specific values of the potentials. Task 2.2.b asks students to find that circuit elements with equal potential at one terminal also do not necessarily have the same voltages as, again, voltages are *potential differences*.

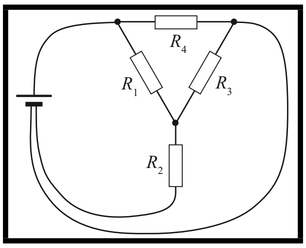
Section 2.3 of the Tutorial (Figure 9.11) asks students to repeat and thereby practice the color coding and to describe a circuit based on

2.3 ***Example***

The following diagram shows a circuit consisting of a battery and four resistors in its actual physical layout.

a. In the circuit, mark all points of equal potential with the same color.

b. Describe the layout of the circuit in terms of series and parallel connections of the resistors or groups of resistors.



c. In the space provided at right, draw a circuit diagram using the normal rectangular layout.

Figure 9.11: First half of page 3 of the custom version of the Tutorial *Basic Circuit Analysis*.

parallel and series connections. Finally, students are asked to simplify the circuit diagram.

9.5.4.3 *Part 3: Notation, Network Equations, Limits of the Model*

In Part 3 (shown in the Appendix), the Tutorial seemingly switches focus, discussing the passive sign convention (Section 3.1) and the relation between the elements in a circuit diagram and the equations used to describe the respective circuit (Section 3.2). These sections still refer to the electric potential. Section 4, which discusses the differences between ideal and non-ideal voltage sources, does not refer to the electric potential.

While not recorded explicitly, the notes on problems in and possible changes to the Tutorial suggest that not many students reached this third part of the Tutorial. This observation is not surprising, as many tasks in Sections 1 and 2 are quite difficult. Students are for example often confused how to define series and parallel connections without using current and voltage (task 1.1b).

9.5.5 *Evaluation of the Custom Version of the Tutorial "Basic Circuit Analysis"*

This section describes the evaluation of the custom version of the Tutorial *Basic Circuit Analysis*. As will become clear at the end of this section, students who had participated in the Tutorial were in many cases not able to correctly apply KVL in the context of open switches. Section 9.6 will therefore describe the design of a different Tutorial that proved to be more successful. Due to the clear test results with the custom version of the Tutorial *Basic Circuit Analysis*, its evaluation is not described in as much detail as other evaluations in this thesis.

Seven weeks after the custom version of the Tutorial *Basic Circuit Analysis* was used in the course EE1ME, a test was administered in the course. 311 students participated, most of which likely also had participated in the Tutorial. However, as the self-generated identification codes (SGICs) had not been in use when this test was conducted, the percentage of students that participated in both the Tutorial and the test could not be measured.

Two questions on the first page of the test are shown in Figure 9.12 and were designed as a post-test to the Tutorial. Students were initially told they had 10 minutes to complete the test. This time was later extended to 12 minutes so that most students were able to finish the test. Consequently, blank answers to the first two equations of the test will likely be a result of students not knowing the answer to the question and not a lack of time.

Task a) asked students to rank the voltages V_{AB}, V_{AC}, and V_{AD} by their absolute value and indicate any voltage that was zero. Task b) asked students to rank the nodes A to D by their potential. The an-

Table 9.1: Overview of correct and most common rankings in the post-test shown in Figure 9.12. Rankings considered correct are printed in green font. N=311.

(a) Voltages

Ranking	Frequency
$V_{AC} > V_{AD} > V_{AB} = 0$	2 %
$V_{AC} > V_{AD} > V_{AB}$	1 %
$V_{AD} > V_{AB} = V_{AC} = 0$	40 %
$V_{AD} > V_{AB} = V_{AC}$	19 %
$V_{AB} = V_{AD} > V_{AC} = 0$	5 %
blank	2 %

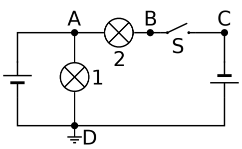
(b) Potentials

Ranking	Frequency
$\phi_A = \phi_B > \phi_D > \phi_C$	1 %
$\phi_A > \phi_B = \phi_C = \phi_D$	18 %
$\phi_A > \phi_B = \phi_C > \phi_D$	9 %
$\phi_A > \phi_B > \phi_C = \phi_D$	5 %
$\phi_A > \phi_B > \phi_C > \phi_D$	5 %
$\phi_A > \phi_D > \phi_B = \phi_C$	5 %
blank	15 %

swers consisted of 27 logically distinct rankings of voltages and 47 logically distinct rankings of potentials. Table 9.1 gives an overview of the most frequent rankings. The correct rankings are printed in green font and were given by only 3% and 1% of the students, respectively.

Of the 219 students who ranked both quantities, 84% gave inconsistent answers. Their ranking of the potentials contradicted their voltage ranking. For example, many students correctly stated $V_{AD} > V_{AB}$, but then answered that the potentials at D and B were equal ($\phi_D = \phi_B$).

1. The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery. The symbol at node D denotes zero potential. The bulbs 1 and 2 are also identical. Switch S is open at first.



Open switch:

a. Rank the three voltages V_{AB}, V_{AC} and V_{AD} by their absolute value. Use the relational operators '>', '<' and '='. State explicitly, if two voltages are equal or a voltage is zero.

Answer:

Reasoning:

b. Rank nodes A to D by their potential ϕ_A to ϕ_D.

Answer:

Explanation:

Figure 9.12: Post-test of the custom version of the Tutorial *Basic Circuit Analysis*. This question was used in EE1ME in 2013/14 (Appendix E.10).

The low frequency of only 3% correct voltage rankings shows that after the Tutorial, the vast majority of students still had difficulties with KVL. No pre-test was conducted for this Tutorial, so it is unclear how many students improved their understanding of KVL through the Tutorial or other instruction at the time. Nevertheless, the post-test results clearly indicate considerable room for improvement in helping students understand KVL. In addition, the high number of logically distinct voltage rankings shows general confusion amongst students about the correct answer.

One method through which the Tutorial was supposed to help students understand KVL was the introduction of the concept of the electric potential. As shown by the test results, students did not learn to correctly use the electric potential with the Tutorial. In the post test, only 1% of students correctly ranked the potentials at nodes A to D, which was supposed to help students understand the voltages in the circuit. The large number of incompatible potential and voltage rankings shows that students did not make that connection.

9.6 DEVELOPMENT OF THE NEW TUTORIAL "POTENTIAL"

As described in Section 9.4, the electric potential provides an easy explanation of KVL and in some cases an alternative to it. The potential thereby might help students overcome many of the misconceptions related to KVL that were documented in Chapter 7. Section 9.5 therefore analyzed several Tutorials that employed the electric potential. While the Tutorial developed by Smith and van Kampen (2011) was considered successful in helping students understand circuits with multiple batteries, the Tutorial *Basic Circuit Analysis* failed in helping students to better understand KVL, possibly because students did not learn to correctly use the electric potential. This section documents the design and analysis of a completely new Tutorial that introduces students to the electric potential and therewith guides them to investigate KVL in different circuit configurations.

9.6.1 *Design Goals*

Based on the considerations about the importance of the electric potential presented in Section 9.4 and the negligible success of the custom version of the Tutorial *Basic Circuit Analysis* presented in the previous section, the design goals for the new Tutorial *Potential* were:

1. Introduce students to the electric potential *and*
2. convince students of the usefulness of the electric potential.
3. Allow students to practice using the electric potential *and*
4. confront students with their misconceptions regarding KVL, focusing on the voltage across open switches.

While the custom version of the Tutorial *Basic Circuit Analysis* had also introduced students to the electric potential (1), their answers in the post-test showed little to no consistency between their answers regarding the electric potential and voltage. Students either incorrectly understood the electric potential or did not see a use in comparing their answers regarding the voltage and the electric potential. Thus, they did not consider the electric potential useful in determining the voltages in the post-test circuit. Design goal (3) will result in students spending more time applying the electric potential and investigating its relations to voltage. Thus, it will help to enforce design goal (2). The repeated application of the electric potential will also increase the likeliness that incorrect understanding about the electric potential will be discovered.

The custom version of the Tutorial *Basic Circuit Analysis* showed limited to no success in helping students correctly rank the voltages in the post-test. While the electric potential is likely to help students identify several misconceptions about KVL, the new Tutorial *Potential* specifically addresses on the common difficulty of the voltage across the open switch (design goal 4). It is hoped that the use of the electric potential in the Tutorial will also focus students' discussions about voltages and KVL on these most important aspects.

9.6.2 *Description of the Tutorial* [12]

After a brief overview of the tutorial, its individual sections will be described in detail. The German original and an English translation of the full Tutorial are printed in Appendix B.8 (p. 361).

The Tutorial *Potential* uses the structural arc *elicit – confront – resolve*, which can also be found in many other Tutorials like *Current and Resistance* and *Voltage*. But unlike most of these Tutorials, the Tutorial *Potential* is built around one large *elicit – confront – resolve* arc that spans the first three pages.

Students' prior knowledge about KVL is elicited through a pre-test embedded in the Tutorial (Section 0). Then, students are introduced to the electric potential. After an examination and familiarization with its properties, students are guided through several steps to analyze the pre-test question using the electric potential, confronting them with their misconceptions about the voltage across open circuits and switches. This confrontation will also highlight the usefulness of the electric potential. The remaining parts of the Tutorial focus on other aspects of the electric potential and its uses in analyzing circuits, allowing teaching assistants (TAs) to help students to resolve

12 The Tutorial described in this section was developed as part of Felix Lehmann's bachelor's thesis, which was supervised by the author of this thesis. A brief description of the Tutorial and an early evaluation have been published previously (Timmermann et al., 2015).

any remaining issues regarding the electric potential, voltage, and KVL.

This Tutorial focuses on circuits in which virtually all potentials are defined by ground and ideal voltage sources. While such circuits might be rare in reality, their potentials are easier to discuss in classroom settings as there is a low number of unknown or arbitrary potentials. Thus, these circuits allow students to focus on the relations between voltages and potentials.

In the following subsections, the individual aspects of the Tutorial and the design decisions made during its development are described in detail.

9.6.2.1 *Integrated Pre-Test Question*

Tutorials and their design are introduced in Section 2.3.4 (p. 26).

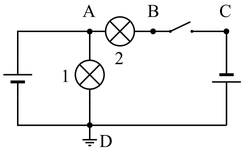
The Tutorial starts with an introductory paragraph and a pre-test. Both are depicted in Figure 9.13. As in all German Tutorials, an introductory paragraph briefly explains the intent of the Tutorial. By stating that the electric potential is introduced "to improve the analysis of circuits", the Tutorial refers back to the previous Tutorials, which also dealt with the modeling of electric circuits. The reference is, however, much weaker than in many other cases, where specific Tutorials are referenced by name.

As can be seen in Figure 9.13, the first part of the Tutorial is the integrated pre-test. In case there is no need to evaluate students' pre-test answers, the Tutorial can be handed out directly. Students would then begin the Tutorial by answering Task 0.1. If students' pre-test answers are to be evaluated, it is best to first hand out a pre-test containing the pre-test question. When the pre-test is collected, students can then be instructed to start with the Tutorial by filling in their answer to the pre-test question. Even if students have forgotten their exact answer, they should still remember the circuit layout and be able to re-answer the question in less than a minute. In both cases, instructors should not interfere with or comment on students' answers to the integrated pre-test. Section 2 of the Tutorial will ask students to check their own

The following Tutorial introduces the concept of the electric potential to improve the analysis of circuits. Additionally, a method is introduced that helps to gain a better overview of a circuit.

0 Pre-Test Answer

0.1 Rank the voltages V_{AB}, V_{AC}, V_{AD}, and V_{BC} by their absolute value. State explicitly, if two voltages are equally large or a voltage is zero. (Try to remember your answer from the pre-test. At a later point in time, you will be have the chance to discuss your answer with other students.)



Circuit from the pre-test

Figure 9.13: Integrated pre-test question in the Tutorial *Potential*.

answers using the electric potential. There, they are explicitly told to discuss their answers with a TA.

The pre-test question was designed to investigate students' understanding of KVL through the voltage across an open switch. As discussed on page 134 in Section 7.4, open switches are one of few circuit elements in basic circuit analysis whose voltage is not related to the current through them. Thus, to determine the voltage across an open switch, KVL has to be used. In order to prevent students from calculating the voltages, but instead use qualitative arguments, the question uses the ranking format. Having students *rank* the voltages V_{AB}, V_{AC}, V_{AD}, and V_{BC} means that the exact values of these voltages are not important. A scaling factor can be applied to all voltages without changing the ranking. Consequently, students only have to be told that the batteries are identical. The source voltage of the batteries does not have to be specified.

The benefits of ranking tasks are discussed in Section 5.3.4.

The circuit of the pre-test question was chosen deliberately to be as simple as possible while still containing the required voltages that are supposed to be ranked. No element of the circuit can be removed without greatly decreasing the difficulty of the question or completely changing it. The circuit was designed so that the correct answer for the voltage across the open switch (V_{BC}) cannot be guessed simply. It is neither $0\,V$, nor the battery voltage. With only one battery, the voltage across the open switch could only be $0\,V$ or the battery voltage. Therefore, both batteries are required. Bulb 1 is used to include V_{AD} in the rankings, which is equal to the battery voltage. Thus, the ranking contains the battery voltage without actually naming it as such. Bulb 1 also obscures the fact that V_{BC} can be determined by following the wire from A to the left, down through the battery and right to D. If bulb 1 were not present, this method of determining V_{BC} would be too obvious. Bulb 2 is also required. It ensures a valid circuit in the case of the switch being closed. If bulb 2 did not exist and the switch were closed, the two batteries would be connected in parallel with reverse polarity. Bulb 2 is also used to include $0\,V$ in the ranking without mentioning it explicitly. The overwhelming majority of students will correctly state that no current flows through bulb 2. Students should then conclude that there is no voltage across bulb 2.

The open switch, obviously, is also required. Its placement, however, is also crucial. The voltages are chosen so one voltage (V_{AB}) is zero, one voltage (V_{AD}) is equal to one battery voltage, and one voltage (V_{AC}) is equal to two battery voltages. To prevent unnecessary complexity, the voltages were chosen to all have a common reference point and all be positive if measured from this common point. To prevent any errors due to students reading the voltages backwards, the question asks to rank the absolute values of the voltages. Since most students' errors in the ranking are caused by their understanding of the voltage across the open switch, the voltage across that switch

(V_{BC}) was added to the ranking. The inclusion of V_{BC} also makes it easier to evaluate students' understanding of the open circuit voltage, even though it might also hint at the main goal of the test.

Considering students' answers in the pre-test, this task is unusually difficult. As will be discussed later (see Table 9.2), only 3% of the students who participated in the pre-test, gave a completely correct ranking. However, in order to elicit students' misconceptions about KVL in general and the voltage across the open switch specifically, a task is needed that students will actually answer incorrectly. A task with a high fraction of incorrect answers is beneficial in this case, as students who answer the task correctly will likely not be confronted with a misconception they might have.

9.6.2.2 *Introduction of the Electric Potential*

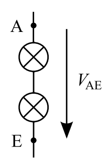
After the integrated pre-test, the Tutorial presents students with a definition of the electric potential (see Figure 9.14). Introducing new concepts by definition is rarely done in Tutorials, as it is either assumed relevant concepts were already introduced during lectures or because the Tutorials are designed in the style of discovery based learning, where prior definitions are not necessary.[13] However, as discussed in Section 9.3 the electric potential is not part of many curricula. Thus, students cannot be expected to be aware of or able to apply it.

The Tutorial uses the electric potential as a tool to help students better understand voltage. The introduction of the potential in the Tutorial reflects this intention. Students are not guided to discover the electric potential and its properties, like they discover Kirchhoff's Current Law (KCL) and KVL in the Tutorials *Current and Resistance* and *Voltage*. Instead, they are presented the electric potential and then guided to use it to discover properties of voltage and KVL.

13 The Tutorial *Current and Resistance* also contains a definition box on the first page. However, that is the first Tutorial on electric circuits and mostly uses the box to define commonly used symbols.

1 The Electric Potential in Circuits

A potential Φ can be assigned to any point on a wire in a circuit. The voltage between two points is the difference of their potentials. Consequently, the unit of both, voltage and potential, is Volt [V]. The following equation and the figure at right show the relation between voltage and potential:



$$V_{AE} = \Phi_A - \Phi_E$$

The voltage V_{AE} is larger than zero, if the potential Φ_A is larger than Φ_E. To determine the potentials in a circuit, one arbitrary point (on a wire) is assigned an arbitrary potential. All other potentials are determined relatively to that first potential. The positive terminal of a battery has a potential that is *one battery voltage* higher than that of the negative terminal.

Figure 9.14: Definition of electric potential in the Tutorial *Potential*.

Only after the definition of the electric potential, the Tutorial starts with task 1.1 (see Figure 9.15). In this task students are instructed to color-code the circuit using the following instructions:

> Start at an arbitrary point on one wire and mark that point with a colored pen. Mark all points and wires that are not separated from this first point by a circuit element with the same color. Repeat this process with different colors until all points and wires are marked.

These instructions are designed so that students end up with a color coding as shown in Figure 9.15. Students are then asked about the voltage between points with the same color (task 1.2). Since the task stated that wires have zero resistance, there is zero voltage between points with the same color. Consequently, each color represents one potential.[14] Through this task, students find on their own that the colors represent regions of different potentials in the circuit and that the instructions can be used to find areas of equal potential. This observation is used throughout the rest of the Tutorial and thereby reinforced.

Now that the different potentials in the circuit have been colored, students are guided to determine their values and to relate their findings to the previous observations about the brightness of bulbs in different circuit configurations. These tasks are shown in Figure 9.16.

The first of these tasks asks students to assign an arbitrary value to one of the potentials and then determine all other values based on the first one. The procedure to be used is not specified. Informal classroom observations show that many students are unfamiliar with the electric potential and require guidance on how to determine the

14 In some cases, further analysis will reveal that different colors correspond to the same electric potential.

Consider the circuit below. Both batteries can be treated as ideal voltage sources with a source voltage of 1.5 V. The wires have zero resistance and all bulbs are identical. The letters A through H mark points on the wires.

1.1 To obtain a better overview of the circuit, color coding will be used. Start at an arbitrary point on one wire and mark that point with a colored pen. Mark all points and wires that are not separated from this first point by a circuit element with the same color. Repeat this process with different colors until all points and wires are marked. If possible, use red at point A and blue at point E.

1.2 If wires have no resistance, what is the voltage between two points on the same wire? What can you tell about points with the same color? *Voltage between points on same wire: 0 V*
⇒ same color = same potential

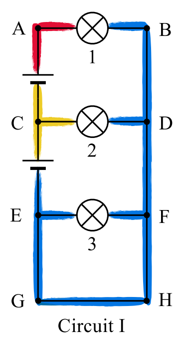


Figure 9.15: Example of a completed color-coding task in the Tutorial *Potential*.

values of the potentials, which was not unexpected. The task does not state a specific procedure so that students must discuss their approach with each other and the instructors, with the intent of resulting in a less formulaic and more substantive understanding of the electric potential. Task 1.4, which asks students to compare the potentials with the battery voltages, was added as a safeguard to prevent students from accidentally determining incorrect values for the potentials.

Tasks 1.5 to 1.7 then ask about the brightness of the bulbs and how it relates to the potential differences across them. When "potential difference" is understood as "voltage", these tasks can be solved based on what students have learned in the Tutorial *Voltage* or their lectures. The goal of the task is to have students use the relationship between voltage and the electric potential while analyzing the circuit. Task 1.7 is designed to highlight bulb 3 being short-circuited. Many students do not realize that the bulb does not glow.

An investigation into students' understanding of short circuits is presented in Section 7.6 (p. 159).

9.6.2.3 *Confrontation with Pre-Test Answer*

As can be seen in Figure 9.17, Section 2 of the Tutorial starts with a box introducing the ground symbol. The ground symbol is deliberately only introduced after students have familiarized themselves with the electric potential. This way, students have to consider and discuss the arbitrary offset of electric potentials in Section 1.

After students have been introduced to and worked with the electric potential, Section 2 asks them to apply it to the circuit from the

1.3 Assign an arbitrary potential to *one* of the colors. Try to determine all other potentials based on the first one.

1.4 Verify that the potentials you have assigned are not in conflict with the source voltages of the batteries. In case of inconsistencies, adjust the potentials accordingly.

1.5 Determine the potential differences across all three bulbs.

1.6 Rank the bulbs by their brightness. What relationship between potential difference and brightness can be used for this?

1.7 Is it correct to assume that the potentials at the terminals of a bulb (as those of a voltage source) are always different from each other? Explain.

Discuss your answers to Part 1 with a Tutorial instructor.

Figure 9.16: Second half of Section 1 in the Tutorial *Potential*.

2 Voltages across open Switches

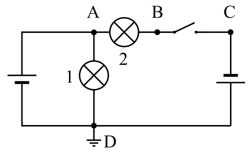
The next circuit contains a grounding (or earthing). By convention, the grounding is assigned a potential of 0 V and all other potentials are measured relative to this ground potential.


Grounding

Consider the following circuit, which contains identical bulbs, ideal batteries with a source voltage of 1.5 V, a grounding, and switch. The switch is in the open position.

2.1 Colorize all points and wires by the color-coding introduced in Section 1.1.

2.2 Assign a potential to each color.



Circuit II

2.3 Check if the values of the potentials fit the potential differences of the batteries. Correct your answer in 2.2 if this is not the case.

2.4 Is bulb 2 *brighter*, *equally bright*, or *dimmer* than bulb 1? Explain.

2.5 What can you conclude from the brightness of bulb 2 about the potential difference across bulb 2? Does the brightness fit the open switch?

2.6 Rank the voltages V_{AB}, V_{AC}, V_{AD}, und V_{BC} again by their absolute value. Use the potentials to determine the voltages. Does your answer match the answer you gave in Section 0.1?

Discuss your findings with a Tutorial instructor.

2.7 What is the voltage between both ends of the open switch?

Figure 9.17: Section 2 of the Tutorial *Potential*. The dashed line indicates a page break.

pre-test. Tasks 2.1, 2.2, and 2.3 mirror tasks 1.1, 1.3, and 1.4 from the previous section. This similarity was employed intentionally to reinforce the three steps used in these tasks as the standard approach to analyzing a circuit with the electric potential.

With task 2.4, the Tutorial switches to questions about the bulbs' brightnesses. It is likely that students answer tasks 2.4 and 2.5 not based on the electric potential but based on what they have learned in the previous Tutorials. The goal of these two tasks is to establish that the voltage across bulb 1 is one battery voltage and that no current flows through bulb 2. Students should be able to make both statements after they have worked through the Tutorials *Current and Resistance* and *Voltage*.

3 Circuit with Closed Switch

The switch in circuit II is now closed.

3.1 Draw the circuit with the closed switch in the box at right. Mark points A through D.

Circuit III

3.2 Do the following absolute voltages *increase*, *stay the same*, or *decrease* by closing the switch?

$|V_{\mathrm{AD}}|$:

$|V_{\mathrm{AC}}|$:

$|V_{\mathrm{AB}}|$:

$|V_{\mathrm{BC}}|$:

3.3 What is the same about the two voltages that do not change?

3.4 What is the same about the two voltages that do change?

Discuss your answers to 3.3 and 3.4 with a Tutorial instructor.

3.5 Is bulb 2 *brighter*, *equally bright*, or *dimmer* than bulb 1 after the switch as been closed?

3.6 Are the following bulbs *brighter*, *equally bright*, or *dimmer* than they were before the switch was closed? Explain.

Bulb 1:

Bulb 2:

Figure 9.18: Section 3 of the Tutorial *Potential*.

Task 2.6 asks students to again rank the voltages from the pre-test, this time based on the electric potentials determined in task 2.2. Here, students are confronted with their answer in the pre-test, and thus in most cases their misconceptions regarding KVL and the voltage across open switches. Task 2.7 is used to call special attention to the voltage across the open switch, ensuring that the incorrect answer of zero voltage across the open switch is not overlooked. The prompt to discuss the answer with an instructor was inserted to ensure students do not miss their conflicting answer, by e. g. simply repeating their answer from the pre-test without checking the potentials.

While the *elicit* part of the Tutorial was ensured by the pre-test, tasks 2.6 and 2.7 are the *confront* part. The *resolve* part is not achieved through specific tasks in the Tutorial. Rather, it is expected this function is performed by group discussions among students, discussions with TAs, and partly by discussions around Section 3 of the Tutorial.

9.6.2.4 *Further Examination of the Circuit*

Section 3 of the Tutorial, shown in Figure 9.18, lets students analyze the circuit with the switch closed. The goal of this task is to help students recognize that closing and opening a switch also affects the voltage of other circuit elements. To familiarize themselves with the modified circuit, students are first asked to draw the circuit with the switch closed.

Task 3.2 then asks students to determine if the voltages they ranked before, i. e. V_{AB}, V_{AC}, V_{AD}, and V_{BC}, have changed. It is expected that students use the electric potential to answer this question. However, since they had the opportunity to practice this approach two times before, the individual steps are not repeated. If students do not use the electric potential to find their answer, the instructor called to check the answers of tasks 3.3 and 3.4 will likely ask the students to apply the electric potential.

The goal of tasks 3.3 and 3.4 was to highlight that the voltages that do not change (V_{AB} and V_{AC}) are fixed by the batteries. For both voltages there is a path between their start and end point that only passes along wires (which have no voltage drop) and batteries (which have a fixed voltage drop). For the other two voltages (V_{AD} and V_{BC}) no such path exists. Consequently, these other voltages depend on the rest of the circuit.

The concept of alien knowledge is also discussed in the context of threshold concepts in Section 10.1.2 (p. 275).

The 2014 version of the Tutorial contained one single question instead of tasks 3.3 and 3.4. It prompted students to "explain why some voltages change and some do not." As many students seemed to struggle with that question and discussions with students suggested that the idea of some voltages being fixed could be *alien*, i. e. completely new, for many students, the question was changed in 2015.

Task 3.5 mirrors task 2.4. It and task 3.6 are included to help students understand the change of brightness of bulb 2. The voltage across bulb 1 is fixed by the left battery. The voltage between A and C is fixed to two battery voltages. This voltage, in turn, can either drop across the switch or across bulb 2.

9.6.2.5 *Analysis of Unknown Electric Potentials*

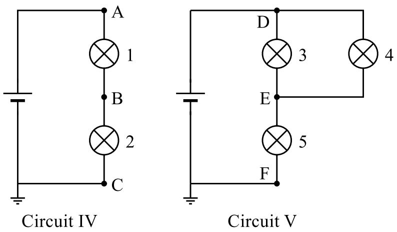
The main *elicit – confront – resolve* arc of the Tutorial only spans Sections 0 to 3 and thus only the first 3 of 4 pages. This design decision was deliberate. During a normal recitation section of about 90 minutes, students usually are able to complete about 3 to 4 pages of a Tutorial. Thus, many Tutorials are designed so that the most important pieces of information are covered on the first three pages. The fourth page then allows the faster groups to further develop the topic. Figure 9.19 shows this fourth page, covering the case of electric potentials that are not determined by wires and batteries alone.

4 Not explicitly defined potentials

All potentials in the previous circuits could be determined by considering only the circuit elements. With more complex circuits, additional methods have to be used to fully analyze a circuit.
Considering the bulbs to behave as non-ohmic (non-linear) resistors, the possible values of the potentials will be narrowed down systematically.

The circuits at right contain identical bulbs. Both batteries are identical and have a constant source voltage of 1.5 V.

4.1 Is it possible to quantify all potentials? If this is not the case, estimate a value. Explain how you made your estimate.



4.2 Rank Φ_A, Φ_B, and Φ_C by their value. Rank Φ_D, Φ_E, and Φ_F by their value.

4.3 Rank bulbs 1 through 5 by their brightness. How do the brightnesses of the bulbs in circuit IV compare to those in circuit V?

4.4 Consider your answer to 4.3. Is Φ_E *larger*, *equally large*, or *smaller* than Φ_B?

Discuss your answers to Parts 4.3 and 4.4 with a Tutorial instructor.

4.5 Determine Φ_B and Φ_E for the case that the bulbs are ohmic (linear) resistors.

4.6 Are your results for the special case of ohmic resistances the same as for the general case in Part 4.4?

4.7 Does the resistance of the identical bulbs influence the potentials Φ_B and Φ_E? Explain.

Contrary to the assumption in Part 4.5, bulbs are *not* ohmic resistors. Their properties are further examined in the Tutorial *Basic Circuit Analysis*.

Figure 9.19: Section 4 of the Tutorial *Potential*.

9.6.3 *Evaluation of the Tutorial*

The Tutorial *Potential* was evaluated over a span of five years. In this time the course EE1ME, where the Tutorial was tested, had three different instructors. As the effect of the Tutorial depended on the instructor, the analysis is split into three parts. Section 9.6.4 will present the evaluation results from 2015 and 2016, when instructor A taught the course, Section 9.6.5 will present the evaluation results from 2017 and 2018, when instructor B taught the course, and Section 9.6.4 will present the evaluation results from 2019, when instructor C taught the course.

As students in the course could not be split into a control and an intervention group, a "fake" control group had to be constructed using the SGICs.

9.6.3.1 *"Fake" Control Groups*

Ideally, to test the effect of an intervention such as a Tutorial, the cohort under investigation is split randomly into two groups: A control group, which is taught conventionally, and an intervention group, which is taught using the intervention. Both groups are given a pre- and a post-test at the same time. As the cohort was split randomly, the pre-test results of both groups, which were treated identically up to this point, should be similar. The intervention is considered a success if the intervention group's increase in performance from the pre- to the post-test is larger than that of the control group. While this approach is ideal from a scientific perspective, it can be quite problematic from an educational and institutional perspective.

All students in a course must take the same exam. To provide a fair test, i. e. equal chances to pass the exam, students must be offered the same support for subject matter that is tested in that exam. Thus, if an intervention covers subject matter that is relevant to the exam, all students must be able to participate in that intervention.

The Tutorial *Potential* was tested in the course EE1ME. No other comparable course was available. As the core issue of the Tutorial, KVL in simple circuits, is central to the course, every student must have the same opportunity to use the Tutorial. Every student in the course EE1ME was supposed to participate in the intervention.

The use of Tutorials in lectures at TUHH is described in Section 4.3 (p. 57).

In the course EE1ME, a pre-test was administered at the start of a lecture. Right after the pre-test, the Tutorial was handed out for students to work on. A few weeks later, a post-test was administered in a lecture of that same course. Using the SGIC described in Section 6.1, it was possible to identify tests which belonged to students who participated in only the pre-test, the pre- and the post-test, and only the post-test. As the Tutorial was handed out directly after the pre-test was collected and no student left the lecture hall in between these two events and the number of pre-tests collected was identical to the number of students who were present during the pre-test, all students who handed in a pre-test also participated in the Tutorial.

Using these observations and the SGICs, it is possible to split the students who participated in the tests into an intervention group and a "fake" control group. The composition of these groups is shown in Figure 9.20. Students who participated in both the pre- and post-test also participated in the Tutorial. These students can be considered the intervention group (green arrow in Figure 9.20). The control group actually consists of two distinct groups and is therefore not a typical control group. These groups are the students who only partic-

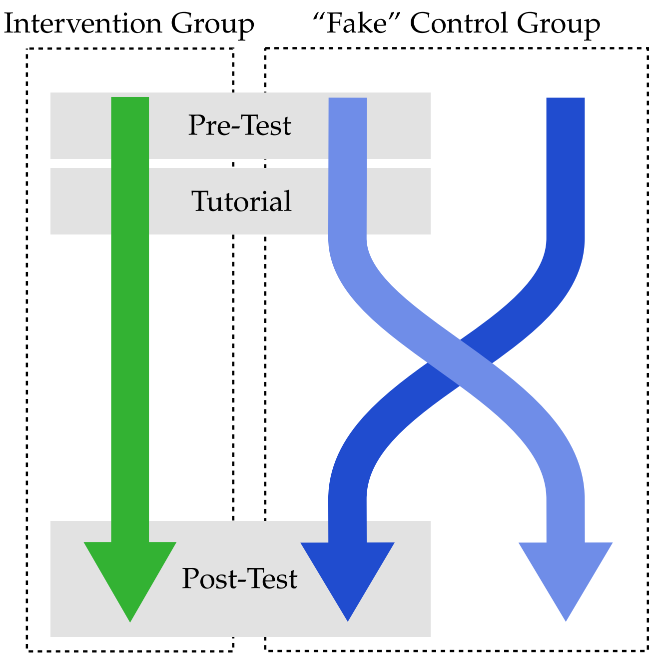


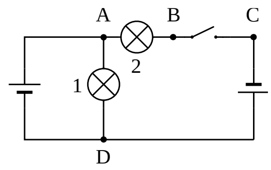
Figure 9.20: Intervention and "fake" control group for evaluation of the Tutorial *Potential*.

ipated in the pre-test[15] (light blue arrow) and the students who only participated in the post-test (dark blue arrow in Figure 9.20). While these two sub-groups consist of different students, there is no known indication that their members are fundamentally different. They simply missed different lectures. It could be argued that the students in the intervention group are different from the students in the control group, since they were present during *both* tests. However, they could have missed any of the other lectures. It could be reasoned that their higher attendance indicated an advantage compared to the students in the control group, as they showed more persistence in their studies. On the contrary, it could also be reasoned that it indicated a disadvantage, since they might have felt the need to attend more lectures. Except for the intervention, there is no known indication that the control and intervention groups will perform differently.

The following subsections compare the pre- and post-test results of these two groups using different pairs of tests. The evaluations are discussed separately for the years 2015 and 2016, 2017 and 2018, and for 2019. In each time-span a different instructor taught the course EE1ME.

15 The students in the control group, who "only participated in the pre-test" actually also participated in the Tutorial. As they did not participate post-test, the effect that the Tutorial had on them cannot be determined. For this evaluation they can be considered to not have participated in the Tutorial.

Task 2



The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The short line denotes the negative terminal of the battery. Bulbs 1 and 2 are identical, the switch is open.

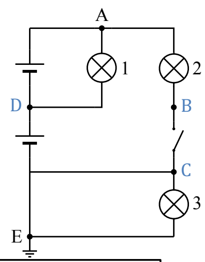
With the switch in the open position:

Rank the voltages V_{AB}, V_{AC}, V_{AD}, and V_{BC} by their absolute value. If two voltages have the same absolute value or one voltage is zero, state this explicitly. Use the relational operators >, <, and =.

Briefly explain your reasoning.:

(a) Pre-test

Task 2



The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery, the short line the negative terminal. Bulbs 1 to 3 are identical, node E is connected to ground.

The switch is in the open position.

a. Rank the voltages V_{AB}, V_{AC}, V_{AD} and V_{CD} by their absolute value. Use the relational operators >, < and =. If two voltages have the same absolute value or one voltage is zero, state this explicitly.

Briefly explain your reasoning.

b. Rank nodes A to E by their electric potentials Φ_A to Φ_E. Use the relational operators >, < and =. If two potentials have the same absolute value or one potential is zero, state this explicitly.

Briefly explain your reasoning.

(b) Post-test

Figure 9.21: Pre- and post-test question matching the integrated pre-test in the Tutorial *Potential*. The blue labels in the post-test circuit have been reordered to be electrically identical to those in the pre-test circuit. The original labeling can be found in Appendix E.

Table 9.2: Frequency of voltage rankings in the pre- and post-test of the Tutorial *Potential*. Data for instructor A. The tests are shown in Figure 9.21. Rankings are only listed when given at least 3% of students. Rankings considered correct are printed in green font.

	Frequency	
	Pre-Test	Post-Test
Ranking	N = 561	N = 381
$V_{AD}>V_{AB}=V_{AC}=V_{BC}=0\,V$	31 %	14 %
$V_{AD}>V_{AB}=V_{AC}=V_{BC}$	6 %	3 %
blank	17 %	7 %
$V_{AC}=V_{BC}>V_{AD}>V_{AB}=0\,V$	3 %	11 %
$V_{AC}=V_{BC}>V_{AD}>V_{AB}$	1 %	4 %
$V_{AB}=V_{AD}>V_{AC}=V_{BC}=0\,V$	3 %	0 %

9.6.4 *Evaluation in 2015 and 2016 (Instructor A)*

Following positive results in initial tests, the main analysis of the Tutorial *Potential* was conducted in the course EE1ME in 2015 and 2016 using the pre- and post-test shown in Figure 9.21. 275 and 200 students participated in the 2015 pre- and post-test, respectively. In 2016, 286 and 181 students participated, respectively.

The full tests can be seen in Appendices E.15 (p. 440), E.17 (p. 448), E.19 (p. 456), and E.20 (p. 462).

The pre-test was identical to the integrated pre-test in the Tutorial. The post-test circuit was designed to be electrically identical to the circuit from the pre-test. However, as many circuit elements were rearranged, none of the course's instructors noticed this similarity before analyzing the circuit in detail. Therefore, it is likely that students also did not notice the similarity of the circuits while answering the test.

A large study on student understanding of the voltage across open switches that also used the pre-test is presented in Section 7.4 (p. 133).

While the pre- and post-test circuit are electrically identical, the post-test circuit additionally contains bulb 3. This short-circuited bulb was added to ensure that the circuit in the post-test would not be easier to analyze than the one in the pre-test.

The post-test answers first revealed students' difficulties with short-circuited bulbs investigated in Section 7.6 (p. 159).

The post-test also contains an additional question asking students to rank the potentials in the circuit (Question 2.b). As this question could help students rank the voltages, it was intentionally positioned after Question 2.a. Informal classroom observations show that the vast majority of students work through the quizzes in the order the questions are printed in. Thus, the ordering of the questions ensures that students work on Question 2.a without having familiarized themselves with the circuit or the electric potentials of its wires.

Table 9.3: Comparison of the frequency of correct and blank voltage rankings for the control and intervention group in the pre- and post-test (see Figure 9.21) to the Tutorial *Potential*. Data for instructor A.

Group	Test	N	Ranking: Correct[a]	Ranking: Correct w/o 0 V[b]	Ranking: Blank[c]
Intervention	pre	291	4 %	0 %	15 %
	post	291	14 %	4 %	6 %
Control	pre	270	2 %	1 %	20 %
	post	90	2 %	4 %	11 %

a Logically equivalent to $V_{AC} = V_{BC} > V_{AD} > V_{AB} = 0\,V$.
b Logically equivalent to $V_{AC} = V_{BC} > V_{AD} > V_{AB}$ with no relation to 0 V.
c Including "joke answers" and incomprehensible rankings.

9.6.4.1 *Voltage Rankings*

Students' misconceptions regarding the voltage across open switches are discussed in Section 7.4 (p. 133).

Due to the large number of voltages to be ranked and the complexity of the circuit, there was a large number of different answers. Overall, 121 and 129 logically distinct rankings were given in the pre- and post-test, respectively. The most common rankings are listed in Table 9.2. The most frequent one in both tests is $V_{AD}>V_{AB}=V_{AC}=V_{BC}=0\,V$. This incorrect ranking can likely be explained by students incorrectly believing that there is no voltage across the open switch ($V_{BC}=0\,V$), correctly assuming that no current flows through bulb 2, resulting in $V_{AB}=0\,V$ based on Ohm's Law, and then determining V_{AC} as $V_{AC}= V_{AB}+V_{BC}$. The variant $V_{AD}>V_{AB}=V_{AC}=V_{BC}$ without 0 V was given less often (6% and 3%). Second most frequent were the *blank* answers, which also included the rare unserious answers and rankings in which students clearly did not understand the question, e. g. only ranked voltages they were not asked to rank. The completely correct ranking $V_{AC}=V_{BC}>V_{AD}>V_{AB}=0\,V$ was given by only 3% in the pre-test, but 11% in the post test. The variant of the correct ranking where students omitted the 0 V was given less often (1% and 4%). The rare ranking $V_{AB}=V_{AD}>V_{AC}=V_{BC}=0\,V$ might be caused by a confusion of voltage and potential.

9.6.4.2 *Frequency of Correct and Blank Rankings*

To analyze the effect of the Tutorial, the frequencies of correct and blank rankings in the pre- and post-test can be compared for the intervention and control group. The percentages of these answers are listed in Table 9.3. The control and intervention group performed similarly in the pre-test. In the post-test, the frequency of completely correct answers increased by 10 percentage points in the intervention group, while it stayed the same in the control group. The correct rank-

Table 9.4: Comparison of the frequency of different statements regarding the voltage across the open switch for the control and intervention group in the pre- and post-test (see Figure 9.21) to the Tutorial *Potential*. Data for instructor A. N is the number of students who included V_{BC} in their ranking, the percentages are in respect to N.

			Voltage across open switch (V_{BC})		
Group	Test	N	explicitly larger zero.[a]	implicitly larger zero.[b]	explicitly equal zero.[c]
Intervention	pre	231	9 %	6 %	64 %
	post	257	23 %	16 %	33 %
Control	pre	192	8 %	9 %	59 %
	post	73	8 %	18 %	47 %

a Ranking includes $V_{BC} > 0\,V$
b Ranking does not include 0 V, but V_{BC} ranked larger than at least one other voltage.
c Ranking includes $V_{BC} = 0\,V$.

ings that did not include 0 V increased by 4 and 3 percentage points in the intervention and control group, respectively, so that they are equal after the Tutorial. For the blank answers, both groups show a drop of 9 percentage points with the control group starting at slightly higher values.

There is a clear improvement in the correct answers for only the intervention group, combined with a comparable decrease in blank answers. The same drop in blank answers in the control group, however, does not result in more correct answers for this group. Still, the overall low percentages of correct rankings paint a grim picture. A major reason for these low percentages in both the pre- and post-test, however, is the unusually high complexity of the ranking question. A more focused comparison is possible if only one single aspect of the ranking is analyzed at once. Such a comparison also helps to highlight the effect of the Tutorial.

9.6.4.3 *Voltage Across the Open Switch*

The Tutorial *Potential* was built around an investigation of the voltage across an open switch. Consequently, it should improve students' answers regarding V_{BC}, the voltage across the open switch. Specifically, the incorrect answer that there is no voltage across the open switch ($V_{BC} = 0\,V$) should decrease for the intervention group, as this misconception is addressed specifically in the Tutorial. Students' statements regarding V_{BC} can be extracted from the rankings.

Table 9.4 shows students' answers regarding the voltage across the open switch (V_{BC}) for the intervention and control group. Counted (N) are only students who actually used that voltage in their ranking.

Compared are three groups: Students who explicitly stated V_{BC} to be larger than 0 V, i. e. who included $V_{BC}>0\,V$ in their ranking, students who implicitly stated V_{BC} to be larger than 0 V by ranking the absolute value of V_{BC} as larger than the absolute value of some other voltage, and students who explicitly stated V_{BC} to be zero, i. e. who included $V_{BC}=0\,V$ in their ranking. While these three types of answers are mutually exclusive, other answers were possible, most notably ranking V_{BC} to be one of the smallest voltages without relating it to 0 V.

While students were asked to explicitly state if a voltage was zero (see Figure 9.21), they were not asked to explicitly state if a voltage was larger than zero. Thus to explicitly state that V_{BC} was larger than zero, they had to believe another voltage was zero, state so, and relate that voltage to V_{BC}. While in the correct ranking $V_{AB}=0\,V$ and $V_{BC}>V_{AB}$, there are many reasons why a student might only have implicitly stated V_{BC} to be larger than zero, including the failure to read the instruction to explicitly state if a voltage was zero.

Comparing the changes from pre- to post-test in Table 9.4 reveals several differences between the intervention and control group. While the percentage of students who explicitly stated V_{BC} to be larger than zero more than doubled for the intervention group, it did not change for the control group. The frequency of students who implicitly stated V_{BC} to be larger than zero increased by about the same amount in both groups. The percentage of students who explicitly stated V_{BC} to be zero decreased in both groups, but the decrease in the intervention group is almost three times that of the control group.

The decrease in students who explicitly stated V_{BC} to be zero can be put into context using the data discussed in Section 7.4, which analyzed students' answers to the voltage across open switches and open circuits. Figure 7.16 (p. 151) in that Section summarized the frequency of the belief that the voltage across the open switch is zero for different tests and cohorts. It is repeated on the opposing page as Figure 9.22. Open circuit question 4 (p. 140) in Section 7.4 is the same question as the pre-test used for the Tutorial *Potential*. In fact, some of the data presented in that section are from the cohort investigated in this section. The data from open circuit question 4 are represented by blue markers in Figure 9.22. Blue diamond markers are used for students at TUHH, which all were from the course EE1ME.

To show the effect of the Tutorial *Potential*, Figure 9.23 overlays the percentages of incorrect ($V_{BC}=0\,V$) pre- and post-test answers of the intervention and the control group in Figure 9.22. The solid and dotted lines indicate the average of the $V_{BC}=0\,V$ for the intervention and control group, respectively. The pre- and post-test are distinguished by the filled and empty markers, respectively. Since the vertical position of the markers indicates the number of students in each cohort, only the horizontal distance between the lines is important here.

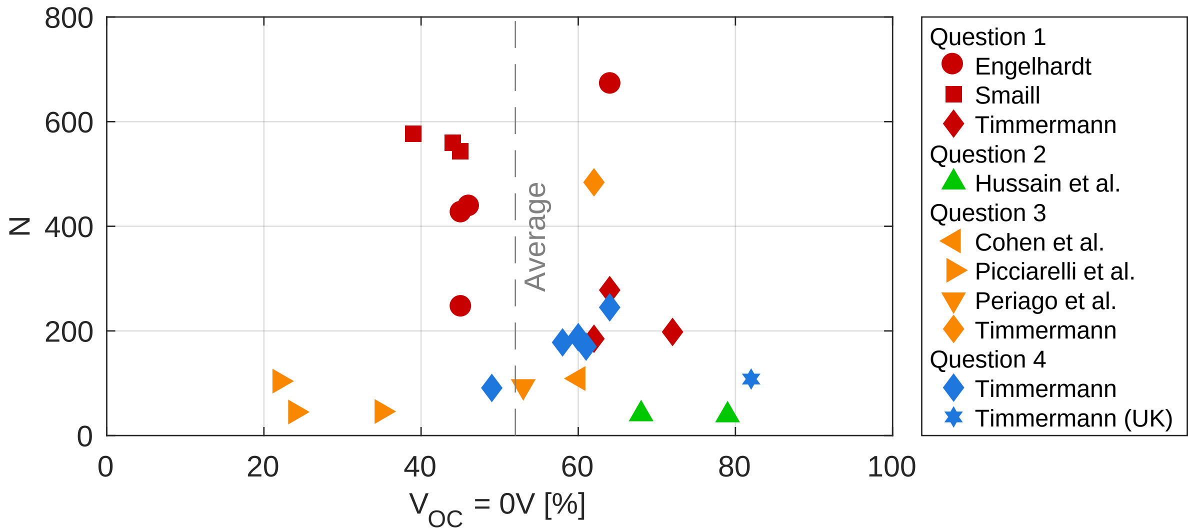


Figure 9.22: Repetition of Figure 7.16 from Section 7.4. Frequency of the belief that the voltage across an open circuit or open switch is zero for different cohorts and questions. The vertical axis indicates how many students in the respective cohort answered the questions. The horizontal axis indicates how many of these students gave the answer 0 V.

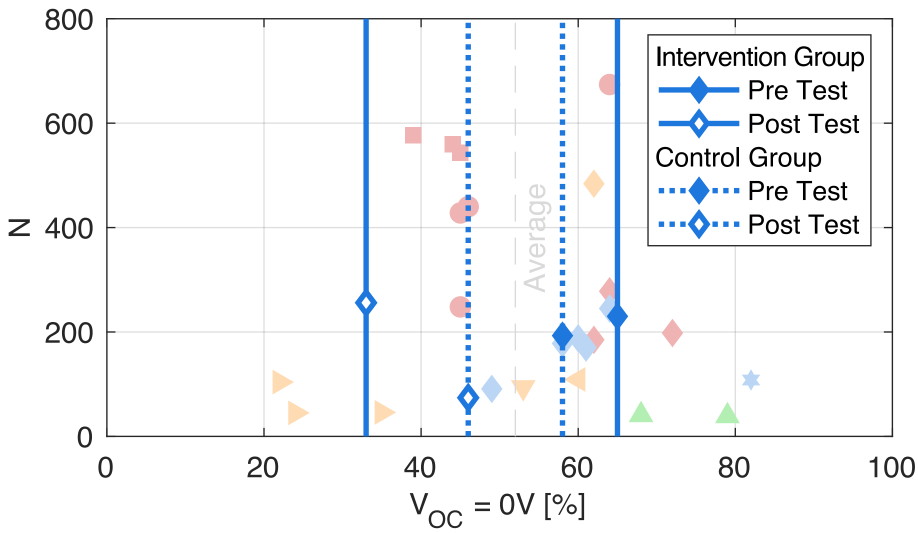


Figure 9.23: Performance of the control and intervention group in the pre- and post-test of the Tutorial on *Potential*. The distance between the solid and dotted vertical lines is the improvement of the intervention and control group, respectively. The vertical position of the markers on each vertical line indicates how many students in each group gave an answer to the respective question. As not all students answered all questions and the control group consists of two independent groups, the group sizes vary. For reference, the data points from Figure 9.22 (see above) are shown in the background.

Table 9.5: Comparison of the frequency of statements about the voltages across the batteries (V_{AC} and V_{AD}) for the control and intervention group in the pre- and post-test (see Figure 9.21) to the Tutorial *Potential*. Data for instructor A. N is the number of students who included V_{AC} and V_{AD} in their ranking. The percentages are in respect to N.

Group	Test	N	Correct ($V_{AC} > V_{AD}$)	Incorrect ($V_{AC} \leqslant V_{AD}$)
Intervention	pre	218	15 %	83 %
	post	253	48 %	47 %
Control	pre	188	14 %	82 %
	post	71	37 %	54 %

The distance between the solid lines can be seen as the improvement of the intervention group, regarding the answer $V_{BC} = 0\,V$. The distance between the dotted lines then is the improvement of the control group. Even though the control group performed better than the intervention group in the pre-test, it performed worse in the post-test. The distance between the solid lines is significantly larger than that between the dotted lines, showing the much larger improvement for the intervention group.

In the pre-test, the intervention group performed worse than most other cohorts shown in Figure 9.23. In the post-test, it performed better than most cohorts. The Tutorial's effect on students' understanding of the voltage across open switches thus was larger than the spread observed between different courses.

9.6.4.4 *Voltages Across the Batteries*

Another relevant evaluation of the ranking focuses on the voltages across the batteries. Table 9.5 shows students' rankings of the voltages V_{AC} and V_{AD}. Points A and D in the circuit are connected to two ends of a single battery. Points A and C are connected to two ends of the series connection of both batteries. Thus, the voltages V_{AD} and V_{AC} are defined by the battery voltages and can be determined by counting the batteries between the respective points. V_{AC} is larger than V_{AD}, as it is the voltage across both batteries.

Table 9.5 presents the percentage of students who correctly and incorrectly related V_{AC} to V_{AD} for the control and intervention group. As not all students who used V_{AC} and V_{AD} in their ranking also related the two quantities, the percentages in each row do not add up to 100%. The percentage of correct relations was quite low in the pre-test, which likely was caused by many students determining V_{AC} along the path of bulb 2 and the open switch which they believed to have

Table 9.6: Frequency of different potential rankings in the post-test (see Figure 9.21b) of the Tutorial *Potential*. Rankings are only listed when given by at least 3% of students. Rankings considered correct are printed in green font.

	Frequency	
	Intervention	Control
Ranking	N = 290	N = 91
blank	23 %	49 %
$\phi_A = \phi_B > \phi_D > \phi_C = \phi_E = 0\,V$	12 %	4 %
$\phi_A = \phi_B > \phi_D > \phi_C = \phi_E$	8 %	2 %
$\phi_A > \phi_D = \phi_B > \phi_C = \phi_E = 0\,V$	3 %	0 %
$\phi_A > \phi_D > \phi_B = \phi_C = \phi_E = 0\,V$	3 %	1 %

zero voltage across. The percentage of correct relations increased for both groups in the post-test. However, the increase was larger for the intervention group.

These results show that the Tutorial helped students to correctly determine the voltage across not only the open switch, but also other voltages in the circuit that were not part of closed loops, but set by voltage sources.

9.6.4.5 *Potential Rankings*

The custom version of the Tutorial *Basic Circuit Analysis* described in Section 9.5.4 failed to improve students' understanding of KVL. After the Tutorial, almost no student was able to correctly rank the voltages in the post-test described in Section 9.5.5. One main reason for this failure was seen in the Tutorial not helping students understand the electric potential. In contrast, the Tutorial *Potential* was successful in reducing students' difficulties with the voltage across open switches. Like the Tutorial *Basic Circuit Analysis* it also used the electric potential as a tool for students to investigate the voltages in a circuit. Consequently, students must have learned to use the electric potential through the Tutorial *Potential*.

This assumption can be verified using the post-test, which asked students to rank the potentials in the circuit. The most frequent rankings of the electric potential in the post-test are shown in Table 9.6. While the blank ranking is most common, the second and third most common rankings are the correct rankings for both the intervention and control group. There is, however, a stark contrast between the two groups, with students in the intervention group performing much better in the potential ranking.

While these differences between the control and intervention group show that the Tutorial helps some students to understand and apply the concept of the electric potential, the gains in regards to the voltage rankings and the voltages across open switches are in many cases larger than the differences between control and intervention group regarding the potential rankings. Thus, it is likely that it is not the understanding of the concept of the electric potential alone that improves students' understanding of voltages. Likely, other aspects of the Tutorial, like the comparison of different voltages and students' discussions of these also contribute to their understanding.

9.6.5 *Evaluation in 2017 and 2018 (Instructor* B*)*

In 2017 and 2018, a different instructor (instructor B) taught the course EE1ME. In these two years, three different tests were used: The pre-post-test combination reported upon above (Section 9.6.4) was used again in 2018. Two different pre-post-test combinations were used in 2017.

9.6.5.1 *Repetition of Prior Pre- and Post-Test*

In 2018, the pre- and post-test (see Figure 9.21, p. 246) was repeated in the course EE1ME. The key evaluations of students pre- and post-test rankings are repeated on page 255. The percentages of correct and blank rankings are shown in Table 9.7, the frequency of different statements about the voltage across the open switch V_{BC} is shown in Table 9.8, and the frequency of correct and incorrect statements about the voltages across the batteries (V_{AC} and V_{AD}) are shown in Table 9.9.

As before, the pre-test results of the intervention and control group are comparable in all three tables. Also, the intervention group shows an increase in correct and decrease in incorrect answers, even more so than in 2015 and 2016. However, unlike the years before, the control group also performed much better in the post test.

The cause of this improvement from pre- to post-test in the control group could not be ascertained. While the new instructor used different instructional materials, the content of the course did not change. In an interview, the new instructor confirmed that open circuit voltages were not discussed in lectures between the pre- and post-test and that tasks in the recitation section also did not include any such problems.

As will be seen on the next pages, this effect also occurred with a different test and circuit configuration. Therefore, it is unlikely that the control groups improvement was the result of students having prior knowledge about the post test or its circuit.

Students in the control group exclusively received traditional instruction between the pre- and post-test. Still, in the post-test, they performed better than virtually all of the traditionally taught cohorts

Table 9.7: Comparison of the frequency of correct and blank voltage rankings for the control and intervention group the in pre- and post-test (see Figure 9.21) to the Tutorial *Potential*. Data for instructor B. Categories as defined in Table 9.3.

			Ranking		
Group	Test	N	Correct	Correct w/o 0 V	Blank
Intervention	pre	91	1 %	0 %	1 %
	post	91	27 %	2 %	1 %
Control	pre	110	1 %	1 %	5 %
	post	67	16 %	6 %	10 %

Table 9.8: Comparison of the frequency of different statements regarding the voltage across the open switch for the control and intervention group in the pre- and post-test (see Figure 9.21) to the Tutorial *Potential*. Data for instructor B. N is the number of students who included V_{BC} in their ranking, the percentages are in respect to N. Categories as defined in Table 9.4.

			Voltage across open switch (V_{BC})		
Group	Test	N	explicitly larger zero.	implicitly larger zero.	explicitly equal zero.
Intervention	pre	89	7 %	9 %	64 %
	post	86	33 %	15 %	19 %
Control	pre	99	2 %	5 %	56 %
	post	59	24 %	17 %	25 %

Table 9.9: Comparison of the frequency of statements about the voltages across the batteries (V_{AC} and V_{AD}) for the control and intervention group in the pre- and post-test (see Figure 9.21) to the Tutorial *Potential*. Data for instructor B. N is the number of students who included V_{AC} and V_{AD} in their ranking. The percentages are in respect to N. Categories as defined in Table 9.5.

Group	Test	N	Correct ($V_{AC} > V_{AD}$)	Incorrect ($V_{AC} \leqslant V_{AD}$)
Intervention	pre	86	13 %	86 %
	post	83	58 %	41 %
Control	pre	100	7 %	89 %
	post	55	49 %	44 %

shown in Figure 9.22. It is unlikely that the simple change in lecture slides or the person lecturing caused the improvement. Before the pre-test the students in the control group participated in two Tutorials (*Current and Resistance* and *Voltage*), but as this also applies to some of the other cohorts in Figure 9.22, it likely also had no effect on their performance.

In the author's opinion, the most plausible explanation is that several members of the control group actually also participated in the Tutorial *Potential*, i. e. that the "fake" control group is not a real control group but partially consists of students who should be part of the intervention group. Such an effect would be the result of false-negative matches due to incorrect responses in the SGIC, which cannot be identified after the fact. The relative sizes of the control and intervention group in the different years, however, hint at this theory. In 2015 and 2016, the size of the control group was about ⅓ of that of the intervention group. In 2018 it was about ⅔. This relatively large size of the control group indicates that some of the students attributed to it could actually have participated in the Tutorial. Strangely, the control group in 2017 also was about ⅓ the size of the intervention group. In that year, the control group performed even better (see below). As data gathered with a third instructor in later years (see Section 9.6.6) returned to the original behavior, the occurrence described here is considered a measurement error with the performance of the control group.

9.6.5.2 *Alternative Pre- and Post-Test*

The full tests are shown in Appendices E.24 (p. 472) and E.25 (p. 476).

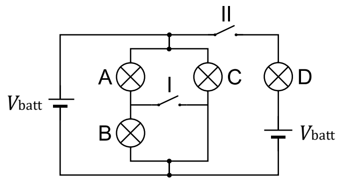
In 2017, the Tutorial was evaluated using a different pre- and post-test which is shown in Figure 9.24. First, students' answers regarding the voltage across Switch I will be analyzed. When considering the voltage across Switch I, the branch consisting of Switch II, bulb D, and the battery on the right can be ignored. That branch was included to obscure the parallel connection between the left battery and bulb C and to be used for an additional question in the post-test.

As bulbs A and B are identical and connected in series, the voltage across both bulbs is the same and equal to one-half of the battery voltage. As Switch I is connected in parallel to bulb B, the voltage across it is *between* $0\,V$ *and* V_{batt}. Students' answers regarding this voltage are shown in Table 9.10. The data are listed separately for the pre- and post-test of the intervention and control group.

As with the other test, the pre-test results of both groups are similar. Both groups improve from the pre- to the post-test, the intervention group more so than the control group. This test shows that the positive data reported above was not simply the result of teaching to the test. Students did not simply understand the specific circuit investigated in the Tutorial *Potential*, but in general improved their understanding of the voltage across open switches.

Task 2

The circuit at right contains two identical batteries, which can be treated as ideal voltage sources with the voltage V_{batt}. The short line indicates the negative pole of the battery. The four bulbs are identical. At first, both switches are open.



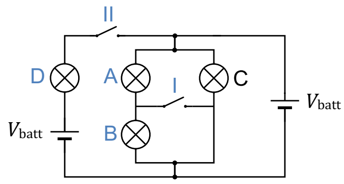
a) The voltage across Switch I is
☐ equal to 0V. ☐ between 0V and V_{batt}. ☐ equal to V_{batt}. ☐ larger than V_{batt}.

Please explain your reasoning!

(a) Pre-test

Task 1

The circuit at right contains two identical batteries, which can be treated as ideal voltage sources with the voltage V_{batt}. The short line indicates the negative pole of the battery. The four bulbs are also identical. At first, both switches are open.



a) The voltage across Switch II is
☐ equal to 0V. ☐ between 0V and V_{batt}. ☐ equal to V_{batt}. ☐ larger than V_{batt}.

Please explain your reasoning!

b) The voltage across Switch I is
☐ equal to 0V. ☐ between 0V and V_{batt}. ☐ equal to V_{batt}. ☐ larger than V_{batt}.

Please explain your reasoning!

(b) Post-test

Figure 9.24: Alternative pre- and post-test to the Tutorial *Potential* used in the course EE1ME in 2017. To avoid confusion, the blue labels A, B, D, I, and II shown in (b) have been altered to be consistent with those in (a). The original labels can be found in Appendix E.25.

9.6.5.3 *Open Switch with* 0 V *Across*

Since the Tutorial *Potential* is built around the idea that there can be a voltage greater than zero across an open switch, it is possible that students actually learn that there *always* is a voltage greater zero across an open switch.

Table 9.10: Comparison of the frequency of statements about the voltage across Switch I in the alternative pre- and post-test (see Figure 9.24) to the Tutorial *Potential*. Data for instructor B.

			Voltage across Switch I	
Group	Test	N	equal to 0 V	between 0 V and V_{batt}
Intervention	Pre	133	38 %	44 %
	Post	133	17 %	56 %
Control	Pre	149	39 %	40 %
	Post	49	31 %	47 %

Student difficulties with parallel voltage sources are discussed in Section 7.3.1 (p. 128).

To test if the Tutorial helped students to correctly identify the voltages across open switches or incorrectly taught them that there always is voltage across an open switch, the circuit in Figure 9.24 was designed so that there is a voltage across the open Switch I, but no voltage across the open Switch II. Bulb D was added to the circuit to ensure that if Switch II were closed, the two batteries would not be connected in parallel. Two batteries (or voltage sources) connected in parallel are an edge-case not discussed in depth in the course EE1ME.

Figure 9.25 presents the fractions of students in the intervention and control group that gave a correct and incorrect answer regarding the voltage across the open Switch I. Also displayed are the fractions of students who gave correct and incorrect answers regarding the voltage across the open Switch II, split into the intervention and control group and correct and incorrect answers regarding Switch I.

Students in the intervention group performed better in every respect. Not only are their answers about the voltage across Switch I correct more often than those of the control group, but also their answers about the voltage across Switch II. The latter is true even for students who determine the voltage across Switch I incorrectly. Interestingly, the percentage of students who correctly determine the voltage across Switch II is roughly the same for those students who correctly determine the voltage across Switch I and for those that do not. This effect is true for both the intervention and control group, indicating that the ability to determine the voltage across switch II is independent of the misconception that there is zero voltage across open switches.

These results show that the Tutorial did not simply teach students that there always is a non-zero voltage across an open switch, but instead increased their ability to correctly determine the voltage across an open switch, regardless of its actual value.

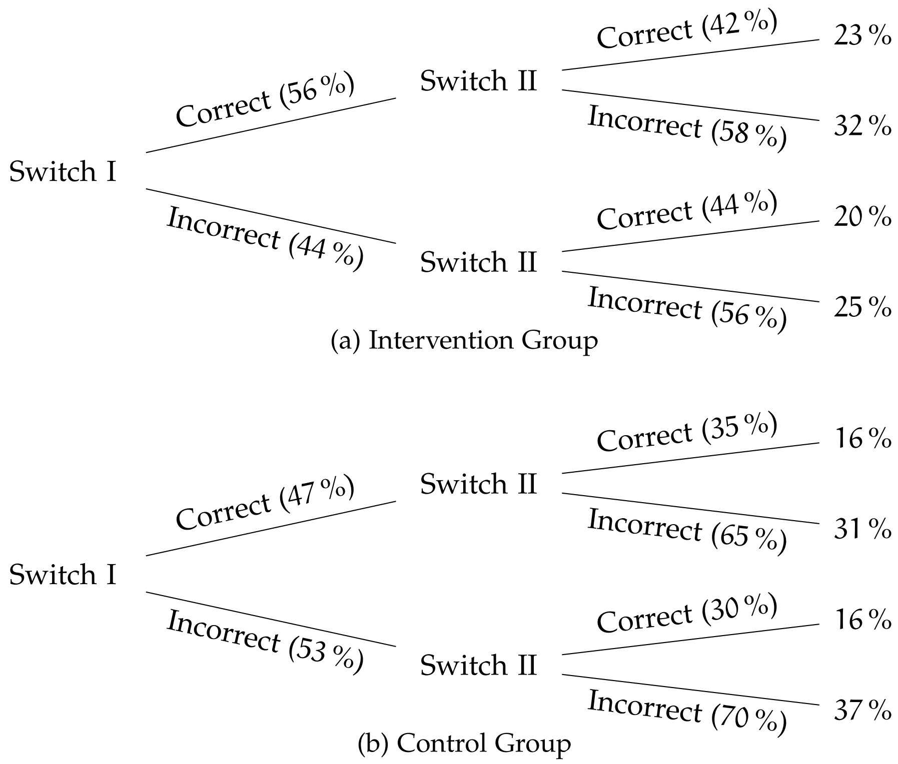


Figure 9.25: Distribution of correct and incorrect answers regarding the voltage across both switches in the test in Figure 9.24 for the control and intervention group.

9.6.5.4 *Question 28 from the* DIRECT

A third combination of a pre- and post-test was also used in the course EE1ME in 2017. The combination of tests is shown in Figure 9.26. This test used Question 28 from the DIRECT concept inventory, which was also part of the analysis on students' beliefs about open circuit voltage in Section 7.4. The pre-test data from this evaluation was included in that analysis. Results for the question can also be found in Figure 9.22.

Figure 9.26a shows the pre-test question given to students. Since all quizzes used in the course EE1ME start with a short explanation of the circuit setup, the question was slightly altered by adding such a description. The state of the switch "(open)" was worded to not draw too much attention to the switch, but still be correct.

The post-test question (see Figure 9.26b) was altered by rotating the circuit by 90 degrees. The direction of rotation was chosen so that in both circuits, point A not only has a higher potential than B, but is also located above point B. This should result in the same answering bias for students who believe the potential to always be higher at higher points in the circuit. Due to a lack of space and to reduce the time required for the post-test, students were not asked to explain their reasoning.

As could be seen in Table 7.15 in Section 7.4.3, students in the pre-test of the course EE1ME answered the question correctly about as often as those from other cohorts. The frequency of the typical incorrect answer, the voltage across the open switch being 0 V, however, was significantly higher.

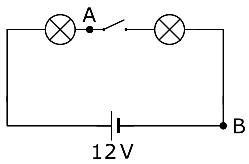
Table 9.11 shows the pre- and post-test answers split for the control and intervention group. Comparing the pre-test answers for both groups, one can see slight, but not relevant, differences. The post-test answers are clearly better, but surprisingly, there again is no clear difference between the control and the intervention group. However,

Task 1

The circuit below contains two identical bulbs, a 12V battery, and a switch (open).

What is the voltage between points A and B?

- ☐ 0 V
- ☐ 3 V
- ☐ 6 V
- ☐ 12 V
- ☐ none of the above



Please give a detailed explanation!

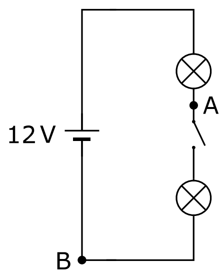
(a) Pre-test

Task 2

The circuit below contains two identical bulbs, a 12V battery and a switch (open).

What is the voltage between points A and B?

- ☐ 0 V
- ☐ 3 V
- ☐ 6 V
- ☐ 12 V
- ☐ none of the above



(b) Post-test

Figure 9.26: Pre- and post-test for the Tutorial *Potential* using question 28 from the DIRECT by Engelhardt (1997).

Table 9.11: Comparison of the frequency of answers to the pre-test and post-test using question 28 from the DIRECT (see Figure 9.26) to the Tutorial *Potential*. Data for instructor B.

Group	Test	N	$V_{AB} = 0\,V$	$V_{AB} = 12\,V$
Intervention	Pre	133	61 %	25 %
	Post	133	23 %	52 %
Control	Pre	149	66 %	26 %
	Post	49	18 %	51 %

while the intervention group performed slightly better in the pre-test, it did perform slightly worse in the post-test.

The substantial improvement of the intervention group was expected. The even more dramatic improvement of the control group, however, was not. Later pre-tests in the course EE1ME in 2018 and 2019 confirmed that the rotation of the circuit did not affect the students' answers. The reason for this effect could not be determined.

9.6.6 *Evaluation in 2019 (Instructor C)*

In 2019, a third instructor took over the course EE1ME. The original pre- and post-tests from Figure 9.21 were repeated. Results are shown on the next page. The test results again were similar to those from 2015 and 2016, albeit with a slightly larger improvement of the control group.

9.6.7 *Changes of Individual Students' Beliefs*

The evaluations shown above only compared group averages. However, using the SGICs, it is also possible to track individual students' answers in the pre- and post-test to investigate how their answers changed from before to after the Tutorial. Since the control group actually consists of two independent groups of students (see Section 9.6.3.1), this analysis can only be performed for the intervention group.

Figure 9.27 presents such an analysis for the student answers shown in Tables 9.4, 9.8, and 9.13 regarding the voltage across the open switch (V_{BC}) in the test from Figure 9.21 (p. 246). At left is the data for the pre-test, at right the data for the post-test. Colors indicate the different answers regarding the voltage across the open switch. Green at top indicates the explicit or implicit statement that the voltage across the open switch was larger than zero, red indicates the explicit statement that the voltage across the open switch was equal to zero, and white at bottom combines the remaining answers. The

Table 9.12: Comparison of the frequency of correct and blank voltage rankings for the control and intervention group in the pre- and post-test (see Figure 9.21) to the Tutorial *Potential*. Data for instructor C. Categories as defined in Table 9.3.

			Ranking		
Group	Test	N	Correct	Correct w/o 0 V	Blank
Intervention	pre	106	5 %	0 %	4 %
	post	106	11 %	10 %	8 %
Control	pre	88	1 %	1 %	13 %
	post	38	3 %	3 %	13 %

Table 9.13: Comparison of the frequency of different statements regarding the voltage across the open switch for the control and intervention group in the re- and post-test (see Figure 9.21) to the Tutorial *Potential*. Data for instructor C. N is the number of students who included V_{BC} in their ranking, the percentages are in respect to N. Categories as defined in Table 9.4.

			Voltage across open switch (V_{BC})		
Group	Test	N	explicitly larger zero.	implicitly larger zero.	explicitly equal zero.
Intervention	pre	99	8 %	6 %	65 %
	post	91	18 %	27 %	25 %
Control	pre	71	4 %	11 %	56 %
	post	30	10 %	20 %	47 %

Table 9.14: Comparison of the frequency of statements about the voltages across the batteries (V_{AC} and V_{AD}) for the control and intervention group in the pre- and post-test (see Figure 9.21) to the Tutorial *Potential*. Data for instructor C. N is the number of students who included V_{AC} and V_{AD} in their ranking. The percentages are in respect to N. Categories as defined in Table 9.5.

Group	Test	N	Correct ($V_{AC} > V_{AD}$)	Incorrect ($V_{AC} \leqslant V_{AD}$)
Intervention	pre	95	13 %	81 %
	post	90	63 %	34 %
Control	pre	71	8 %	87 %
	post	27	33 %	63 %

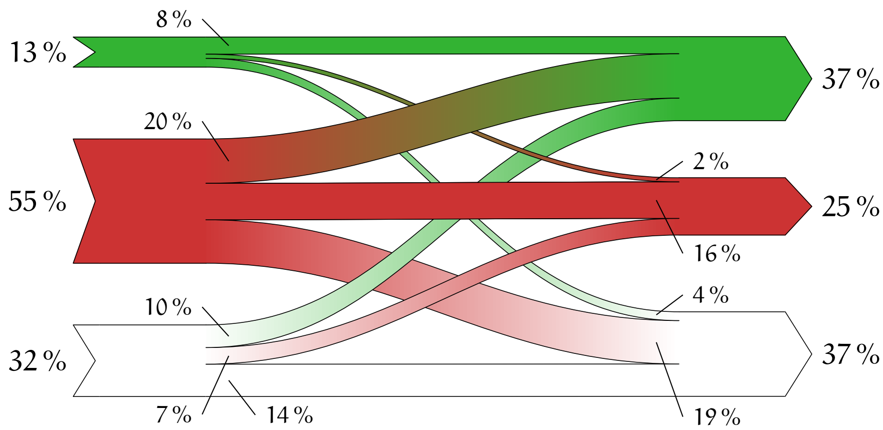


Figure 9.27: Change of students' answers concerning the open switch voltage V_{BC} before and after the tutorial. This figure aggregates data from Tables 9.4, 9.8, and 9.13. Students who explicitly or implicitly expressed V_{BC} to be larger than zero are shown in green at top, students who explicitly state V_{BC} to be zero are shown in red in the middle, and unclear answers are coded in white at the bottom. $N = 488$.

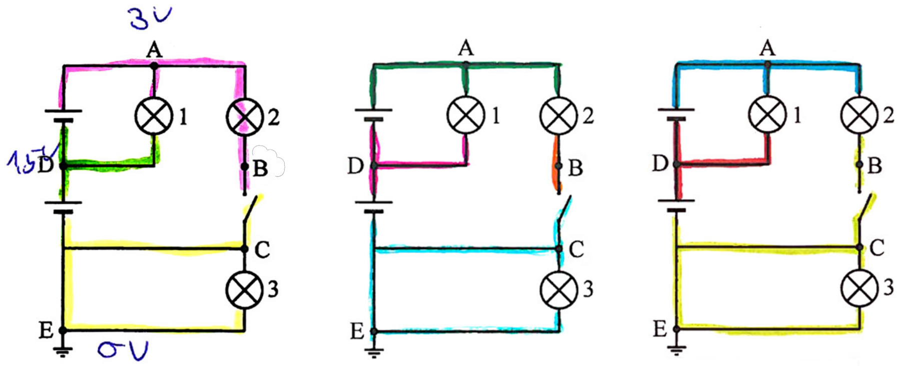
thickness of the arrows indicates the number of students who gave each answer. The diverging and merging arrows in the middle visualize the number of students who changed their answer from the pre- to the post-test. The figure only includes students who included V_{BC} in both their pre- and post-test ranking.

Two key observations can be made about the changes in students' answers shown in Figure 9.27. Firstly, students who correctly believed that the voltage across the open switch was larger than zero mostly did not change their answer. Secondly, most students who incorrectly believed that the voltage across the open switch was zero changed their answer.

These results indicate that the increases in correct answers presented above were not the result of random changes in students' beliefs, but the result of mostly positive changes. Students who had answered correctly in the pre-test mostly did not change their beliefs, while those who answered incorrectly in the pre-test mostly changed their beliefs.

9.6.8 *Students' Use of Color Coding*

Some students used color coding to rank the voltages in the post-test. As students were not asked to use color-coding, these students' answers cannot be considered representative and thus are not evaluated statistically. Still, the color-codings provide insight into students' un-



(a) $\phi_A = \phi_B > \phi_C$ (b) $\phi_A > \phi_B > \phi_C$ (c) $\phi_A > \phi_B = \phi_C$

Figure 9.28: Different color-codings used in the post-test of the Tutorial *Potential*. The labels B, C, and D have been modified to match those in Figure 9.21b.

derstanding of the electric potential. Three select color codings shown in Figure 9.28 will be discussed.

The color coding shown in Figure 9.28a indicates a correct understanding of the electric potential with $\phi_A = \phi_B$ due to no current through and thus no voltage across bulb 2. Consequently, there is a voltage drop across the open switch, i. e. $\phi_B > \phi_C$. The student who used this ranking correctly ranked all voltages as $V_{AC} = V_{BC} > V_{AD} > V_{AB} = 0\,V$.

The color coding shown in Figure 9.28b is in accordance with the instructions provided in the Tutorial. As the wire at B is different from that at A, the relation between the potential ϕ_B and ϕ_A depends on the voltage between them, specifically the voltage across bulb 2. Thus, based on the instructions in the Tutorial, A and B are supposed to be colored differently. Only in a second step, students are supposed to investigate the voltages across circuit elements, such as bulb 2, and identify potentials that have the same value. In this circuit, students were supposed to realize that there is no current through bulb 2 and thus no voltage across it, resulting in $\phi_A = \phi_B$. The student who created the color coding shown in Figure 9.28b, however, assumed that $\phi_A > \phi_B > \phi_C$ and thus incorrectly ranked the voltages as $V_{AC} > V_{AD} > V_{AB} = V_{BC}$.

The color coding shown in Figure 9.28c indicates that the Tutorial did not have the intended effect on the student who used this coding. Although they learned to use the color-coding, they did not overcome their misconceptions about the voltage across open switches. By using the same color at B and C, the student showed that they believed the electric potential at both points to be the same, i. e. $\phi_B = \phi_C$. This belief likely was a consequence of the false belief that there is no voltage across open switches. As the student identified potentials at A and C to be different, they concluded that there must be a voltage across bulb 2, resulting in the voltage ranking of $V_{AB} = V_{AC} > V_{AD} > V_{BC} = 0\,V$.

These observations show that while the color-coding is a useful tool to help students identify electric potentials, it does not necessarily lead to a correct understanding. Students using color coding and the electric potential still make mistakes in determining the voltages in a circuit and some do not succeed in overcoming their misconceptions. Still, even in these cases, the electric potential can help to show students the inconsistencies in their thinking.

9.6.9 *Summary of the Evaluation*

The data presented in Sections 9.6.4, 9.6.5, and 9.6.6 showed that the understanding of the voltages in the investigated circuits greatly improved for the intervention group. The students were not only able to rank the voltages correctly more often after the Tutorial, but also the frequency of correct statements about the voltages across the open switches increased from before to after the Tutorial. Comparing these test results to data from other courses (see Figure 9.23) shows the significance of that change. Before the Tutorial, the control and intervention groups investigated here were among those with the highest frequency of the statement that there is no voltage across the open switch. After the Tutorial, the intervention group was one of the groups with the rarest occurrence of that statement.

For one of the instructors, the control group showed improvements similar to or even greater than those of the intervention group (see Section 9.6.5). However, it is likely that these were caused by the imperfect measurement techniques, i. e. the control groups being "fake" control groups (see Section 9.6.3.1). It seems implausible that the traditional instruction of this particular instructor caused these stark improvements. The results from the other two instructors align with each other, but do not show this pronounced improvement of the control group. The stark improvement of the intervention group can be observed with all three instructors.

The data presented in Figure 9.25 also confirmed that students did not simply learn that the voltage across open switches is always larger than zero, but that the Tutorial helped in general improve students' understanding of the distribution of voltages.

9.7 Summary and Conclusion

After a brief review of the concept of the electric potential in Section 9.1, Sections 9.2 and 9.3 analyzed the use of the electric potential in engineering practice as well as engineering education. It was shown that while the electric potential is only used in some instructional materials on circuit analysis (Section 9.3), it can be commonly encountered in engineering practice, as evidenced by its common use in standards (see Section 9.2.1). The electric potential was also shown to be relevant in the context of circuit design without being referenced by name (Section 9.2.3) and in the context of schematics for digital circuits (Section 9.2.2).

Section 9.4 discussed ways in which understanding the concept of the electric potential could help students overcome specific conceptual difficulties with voltage. In addition to identifying several misconceptions related to voltage (Sections 9.4.1 and 9.4.3) that could be addressed with the electric potential (Section 9.4.2), the section compared circuit analysis with and without the electric potential (Section 9.4.4). For this analysis, mathematical descriptions of the relations between the voltages, currents, and impedances in a circuit were used. The abstraction created by the mathematical descriptions removed the familiarity an electrical engineer usually has with the relations between the voltages, currents, and impedances. The comparison of the mathematical descriptions highlighted the complexity of circuit analysis based on KVL. In comparison, the analysis using the electric potential was shorter and less complex. The observations presented in this section provide the foundation for RQ 3.

RQ 3: *To what extent can an improved understanding of the concept of electric potential help students overcome specific conceptual difficulties with voltage?*

Section 9.5 analyzed existing Tutorials that employed the electric potential. While some Tutorials used the electric potential solely in the context of potential differences (see Section 9.5.1 and 9.5.2), two Tutorials used it to help students overcome specific conceptual difficulties. The Tutorial *Circuits with Multiple Batteries* is derived from a series of worksheets called *Physics by Inquiry* (McDermott et al., 1996). It uses the concept of the electric potential to address student misconceptions regarding circuits with multiple batteries. The Tutorial was considered a success by its authors. Based on their pre- and post-tests, "the introduction of the concept of potential allowed students to systematically discover rules for how circuits with multiple batteries [...] can be modeled [...] [and] increased understanding of the roles current, voltage, and resistance play in [...] electric circuits" (Smith and van Kampen, 2011).

These results contribute to answer RQ 3, asserting that the electric potential can successfully be used to help students overcome difficulties with other concepts. The Tutorial, however, could likely not be used in courses like the ones investigated in this thesis, as the worksheets in *Physics by Inquiry* are designed for courses that use minimal lectures and instead rely on such worksheets. Furthermore, the Tutorial did not address the common misconceptions about the distribution of voltage investigated in Chapter 7, particularly the misconception that there is no voltage across an open switch discussed in Section 7.4.

To address some of these difficulties, a custom version of the Tutorial *Basic Circuit Analysis* had been designed. This version of the Tutorial is discussed in Section 9.5.4. In contrast to the Tutorial *Circuits with Multiple Batteries*, the custom version of the Tutorial *Basic*

Circuit Analysis failed to help students improve their understanding of voltage. Almost no student was able to correctly rank the voltages in the post-test (see Section 9.5.5). One of the reasons for this Tutorial's failure was seen in the Tutorial being a combination of several existing Tutorials, resulting in a lack of focus on one concept. As it was still considered likely that the electric potential could help students overcome many of the difficulties investigated in Chapter 7, a new Tutorial was designed.

Section 9.6.2 described the newly developed Tutorial titled *Potential*. This Tutorial assumes that students are familiar with the concept of voltage, although they likely still hold several misconceptions related to it. It introduces them to the concept of the electric potential and guides them to identify areas with the same potential through color coding. The different potentials and potential differences are then used to support discussions about the voltages across different elements of the circuit. The Tutorial focused especially on the voltage across open switches, which had been established as particularly problematic in Section 7.4.

The evaluation of the Tutorial is presented in Sections 9.6.3 to 9.6.9. Sections 9.6.4, 9.6.5, and 9.6.6 presented test results form the course EE1ME in 2015 and 2016, from 2017 and 2018, and from 2019, respectively. In each period, a different instructor gave the course's lecture. Using SGICs, students were split into an intervention group that participated in the Tutorial and a "fake" control group that did not do so.

The test results of the three cohorts showed that the intervention group, which had used the Tutorial, greatly improved their understanding of the voltage across open switches. In the pre-tests 64%, 64%, and 65% of students believed the voltage across an open switch to be zero. In the post-test, only 33%, 19%, and 25% of students, respectively, believed so (Tables 9.4, 9.8, and 9.13). Figure 9.22 showed the frequency of the belief that there is no voltage across an open switch for many traditionally taught courses. The improvement of the intervention group is as large as the spread in results among the traditionally taught courses, when ignoring some smaller studies. These test results show that the electric potential can be used to help students overcome specific conceptual difficulties with voltage, in this case the false belief that there is no voltage across an open switch. Similarly, the test results showed that the Tutorial helped students to correctly compare other voltages in the circuits (see Tables 9.5, 9.9, and 9.14). Students in the intervention group were also able to correctly identify the voltage across an open switch, when it actually was $0\,V$.

The tests in 2017 and 2018 (Section 9.6.5) also showed strong improvements for the control group. In one case the control group even improved more than the intervention group. This effect was not observed in the earlier or later years, when other instructors taught the course. The most likely explanation of this phenomenon is a measurement error in the formation of the control group.

The evaluation of the Tutorial *Potential* provided an answer to RQ 3. Using the concept of the electric potential, students' false beliefs about the voltage across open switches, a specific difficulty with voltage, was reduced considerably. The frequency of the false belief was more than halved, allowing the cohort to perform better than virtually all traditionally taught cohorts.

INTERPRETATION

10

CURRENT, VOLTAGE, AND POTENTIAL IN THE CONTEXT OF THRESHOLD CONCEPTS

The previous chapter showed that understanding the concept of electric potential can help students overcome specific difficulties with voltage. In particular, it showed that the use of the Tutorial *Potential* improved students' understanding of open circuit voltage. However, introducing a new concept like the electric potential takes time. The Tutorial *Potential*, for example, requires about 90 minutes of class time. This time could also be used to discuss or introduce other concepts in electrical engineering or to allow students to practice the use of concepts already introduced.

When investigating whether or not to include a specific concept in the curriculum, it is therefore not only relevant to determine if that concept can help students to understand subject matter or solve relevant problems. It is also important to determine how "valuable" that concept is compared to other concepts that could be included instead.

Such arguments cannot be made on student performance in tests alone. As shown in the previous chapter, the concept of the electric potential helped students to better understand the concept of voltage. It is safe to assume that the electric potential helped students more than many other approaches not based on the electric potential. But what differentiated the approach using the electric potential from other approaches? Introducing a new concept requires mental resources that could also be spent on the concept of voltage. Would it not be sensible to search for other (Tutorial-based) approaches to help students understand the electric voltage without introducing the electric potential?

This chapter argues why *current flow* and the *electric potential* are both threshold concepts in basic circuit analysis, making their inclusion in the curriculum particularly valuable. Threshold concepts are introduced in the following section.

10.1 THRESHOLD CONCEPT THEORY

The theory of threshold concepts is one of many theories of conceptual change (Davies and Mangan, 2005). It can be used to *categorize* concepts in the curriculum. The theory was introduced by Meyer and Land in 2003 and has since gained widespread attention and sparked discussions about different concepts in many fields of instruction. Through a series of publications Meyer and Land have described and

Different theories of conceptual change were introduced in Section 2.3 (p. 15).

refined the idea of threshold concepts (Meyer and Land, 2003, 2005; Land et al., 2005; Meyer et al., 2008; Meyer and Land, 2008).

Threshold concepts offer a systematic way to discuss the relevance of different concepts in the curriculum, an aspect that can hardly, if at all, be quantified. Thus, it is no surprise that threshold concept theory does not have a quantitative component. Instead, threshold concepts are defined qualitatively through their characteristics.

10.1.1 *Defining Characteristics of Threshold Concepts*

Meyer and Land (2003) characterize threshold concepts through five characteristics. They are *transformative*, *integrative*, *bounded*, *irreversible*, and *troublesome*. These characteristics are defined verbally, and thus allow for some interpretation.[1] So, as Davies and Mangan (2005) suggest: "A search for threshold concepts in a subject necessarily starts with an exploration of [the] definition" of the defining characteristics. This exploration is not only meant as a summary for the reader, but also specifies the author's reading of the five characteristics.

The remainder of this section will discuss this thesis' interpretation of the first four defining characteristics. After their definition and a brief discussion of their importance, they are illustrated using the (threshold) concept of the *Fourier transform*. The fifth characteristic of threshold concepts, being *troublesome*, is discussed in Section 10.1.2.

TRANSFORMATIVE Being transformative is often seen as "the most important distinguishing feature of threshold concepts" (Male and Baillie, 2014). To illustrate this feature, Male and Baillie (2014) explain that "threshold concepts are like gateways for students. They open new ways of thinking and practicing necessary to proceed in a course and, in the case of engineering courses, learn to think, speak, and identify as a professional engineer." This transformation comes in two forms:

Threshold concepts can *transform a learner's understanding* of the world, a particular subject, or parts thereof. Reeping et al. (2017) speak of "a concept that present[s] an entirely new lens to view the physical (and perhaps nonphysical) world". Scott and Harlow (2012) suggest that experts' ways of thinking, like domain specific strategies for problem solving, also are the results of these transformations.

A threshold concept can also *transform a learner's identity*. Meyer and Land (2003) give the example of "specific politico-philosophical insights (for example, aspects of Marxist, feminist or post-structuralist analysis)" that can cause "a shift in [the learner's] values, feeling or attitude". While these extreme changes

1 There exists no commonly accepted operationalization of these characteristics (see Section 10.1.5).

might be reserved to a few subjects, obtaining a professional identity, like the "sense of being an engineer and taking pride in this identity" (Male and Baillie, 2014) is often also seen as such a transformation. Reeping et al. (2017) even discuss whether small feats like knowing how to read the color codes of a resistor fall into this category. However, they conclude that threshold concept literature does not see these aspects as transformative.

INTEGRATIVE Being integrative is a characteristic that describes a threshold concept's relation to other concepts in the same field. A threshold concept "exposes the hidden interrelatedness of phenomenon [sic]" (Cousin, 2006) and thereby "'tie[s]' ideas together in students' mental models" (Reeping et al., 2017). Male and Baillie (2014) suggest two different ways in which a threshold concept can be integrative. The threshold concept can be on the *same level* as the other concepts it connects, being a puzzle piece that connects other pieces. Alternatively, the threshold concept can be on a higher or more *abstract level*, allowing one to see the relation between lower level or more specific concepts. Male and Baillie (2014) claim to have found examples for both types.

BOUNDED Being bounded is a characteristic that describes how a threshold concept relates to the field it is located in. According to Kiley (2009) a threshold "concept does not explain the 'whole' of the discipline, but specific and related aspects of that whole". Other authors, like Male and Baillie (2014) and Reeping et al. (2017) interpret 'bounded' as a concept only applying to one field or discipline. While both have found some concepts that satisfy this criterium, they observe that many concepts are simply examples of more general ideas. The author of this thesis also considers such specific concepts to be threshold concepts.

Meyer and Land (2003) observe that "any conceptual space will have terminal frontiers, bordering with thresholds into new conceptual areas". Thus, threshold concepts are not only inside the bounds of a conceptual area or field, but often also mark the boundaries between different fields.

IRREVERSIBLE This characteristic has two aspects. On the one hand, once learned, the learner is not able to forget a threshold concept, or as Kiley (2009) writes "Once understood it is probable that the concept cannot be 'un-understood'". On the other hand, once having understood, the learner is not able to comprehend not having understood the concept. This aspect is relevant for teaching. Instructors often find it difficult or impossible to envision the learner's perspective, to remember how they saw the world before they went through the transformation of understanding the threshold concept (Meyer and Land, 2003; Cousin, 2006).

A more detailed description of these characteristics with some examples from engineering is provided by Male and Baillie (2014).

Different authors attribute different levels of importance to these characteristics. Meyer and Land (2003) are quite cautious in their language and describe threshold concepts as "possibly" *bounded* and "possibly" *irreversible*. They are less cautious for the characteristics *transformative* and *integrative*. Likely because of this distinction by Meyer and Land, Reeping et al. (2017) label *transformative* and *integrative* as "primary characteristics" and the other characteristics "secondary". Davies and Mangan (2005) describe *bounded* as being derived from the other three.

Some authors also list other characteristics. Male and Baillie (2014) and Reeping et al. (2017) state that threshold concepts are also *discursive* in that they can improve students' ability to communicate using precise language and that they are *reconstitutive*, meaning that they can change students' mental models. These characteristics are discussed by Meyer and Land (2003), but are not part of their list of the characteristics of threshold concepts. In the author's opinion, these characteristics are a result of threshold concepts being transformative. These two additional characteristics are not used in this text.

10.1.1.1 *Example: Fourier Transform as a Threshold Concept*

To illustrate transformativity, integrativeness, boundedness, and irreversibility, these four characteristics will be analyzed in regard to the concept of the *Fourier transform*.[2] In the context of threshold concepts, the Fourier transform is not meant to simply refer to the equation $F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}\,dt$, but to the *idea* that the transformation exists and can be used to move from a time domain view of a signal or system to a frequency domain view. The Fourier transform exhibits the four defining characteristics of threshold concepts, which were discussed above:

TRANSFORMATIVE As Reeping et al. (2017) observe, the Fourier transform "acts as a vehicle to an entire different domain, the frequency domain – a new way to think about signals." While concepts like low pass filters are sometimes used in the time

2 The author was not able to find definitive statements in literature if the Fourier transform is agreed to be a threshold concept. However, Reeping et al. (2017) used it for their explanation of the transformative characteristic. Male and Baillie (2014) claim that transforms in general are a potential threshold concept. The author believes the Fourier transform to be a clear example of a threshold concept in electrical engineering, but that the general concept of transforms might be too broad, i. e. not bounded enough, to be considered a threshold concept. Even if the reader disagrees, the example will help to illustrate the characteristics described here.

domain, their mathematical description only becomes feasible in the frequency domain.

INTEGRATIVE The Fourier transform is an integrative concept in the field of signals and systems in two ways. Firstly, the Fourier transform directly links the concept of time domain and the concept of frequency domain. Secondly, it is integrative on an abstract level. Through the relation between time and frequency domain, one is able to see the relation of many other concepts, like how rectangular signal edges contain infinitely high frequency components and will therefore be "smoothed" in real circuits, as real circuits always act as a low-pass filter due to parasitic resistances and capacitances.

BOUNDED The Fourier transform is not relevant to all of electrical engineering, but limited to the field of signals and systems. Other fields within electrical engineering, like control theory and high-frequency engineering, also use aspects of signals and systems. It could even be argued that the Fourier transform is the frontier that provides the entry to (understanding) signals and systems.

IRREVERSIBLE The Fourier transform, as discussed here in the context of threshold concept theory, does not simply refer to the mathematical equation, but to the idea that such a transformation can be used to move from the time to the frequency domain and vice-versa. The mathematical equation is relatively complex and can easily be forgotten. The idea that there is a frequency domain and that signals can be transformed from the time to the frequency domain using this transform, however, is concise and likely never forgotten once learned.

10.1.2 *Troublesome Knowledge and Threshold Concepts*

In many publications, most prominently Meyer and Land's first paper on threshold concepts (2003), being *troublesome* is named as one of the characteristics of a threshold concept. The author of this thesis agrees with Meyer and Land (2003) that threshold concepts are "[p]otentially (and possibly inherently) troublesome". However, like Davies and Mangan (2005), the author considers threshold concepts to be troublesome because they require a radical shift in the learner's understanding of the subject or even their view of the world (transformative) or because they require the learner to see the relation between seemingly disconnected ideas (integrative). Troublesomeness is a consequence of transformativity and integrativeness, the two primary characteristics of a threshold concept. This interpretation aligns well with many other theories of conceptual change that see the main obstacle to learning a new concept in the necessary modifications of already learned concepts (see Section 2.3).

In threshold concept literature, six different forms of troublesome knowledge are differentiated. While these six forms of knowledge will be briefly described here, they are best explained by Perkins in an updated version (2006) of his stellar *The Many Faces of Constructivism* (1999). Meyer and Land (2003) warn that in many cases, knowledge does not only fall into one but in several of these categories:

Ritual knowledge is knowledge that lacks meaning. Perkins (2006) gives the examples of "routines in arithmetic [...] such as the notorious 'invert and multiply' to divide fractions." Such routines are learned and used repeatedly, often without being understood. Such a use does not necessarily cause any problems. But, the frequent use of such concepts can result in the feeling that they are already understood or that there is nothing to understand, even when deeper consideration would be required. Threshold concepts can be troublesome when they are only learned as mindless operations to be performed without any thinking, when in reality they require to be questioned in order to be truly understood.

Conceptually difficult knowledge regularly occurs in mathematics and science (Perkins, 2006), where ways of thinking are required that are "inconsistent with our experience in life" (Male and Baillie, 2014). These experiences cause misconceptions[3] that hinder the correct understanding of the concept in question. Male and Baillie (2014) additionally suggest that a concept that misses an equivalent in the everyday life can also be conceptually difficult knowledge. They suggest the Fourier transform as an example, which they claim to be troublesome as there is no frequency domain in every-day observations.

The idea of misconceptions was introduced in Section 2.3.3 (p. 21).

Foreign or *alien knowledge* "comes from a perspective that conflicts with our own. Sometimes the learner does not even recognize the knowledge as foreign" (Perkins, 2006). As in the case of conceptually difficult knowledge, alien knowledge is caused by a "disconnect" between one's perception of the world and reality. In the case of conceptually difficult knowledge one's perception *of the concept to be learned* does not align with reality, which causes misconceptions about the respective concept, which must be overcome. In the case of alien knowledge, the "misconception" is one step removed from the concept to be learned. One's perception of *one concept* makes it difficult to learn *another concept*, because the first concept must be understood correctly to understand the second concept. Perkins (2006) mentions value systems associated with certain professions as an example for alien knowledge. The values held by members of a certain profession often are the result of specific conditions (the "concepts" that must be understood), but these values are often encountered in completely different situations.

3 Perkins (2006) does not use the term 'misconception', but his description of the effect these experiences have on learning line up with the definition of misconceptions presented in Section 2.3.3.

Troublesome language was introduced by Meyer and Land (2003) as another form of troublesome knowledge. Many (professional) communities have developed a specialized language by inventing new words (technical terms) or loading common words with additional, subject specific meaning. Uninitiated learners will, in the first case, be unable to understand these words and, in the latter case, possibly remain unaware of their non-understanding.

Inert Knowledge, as Perkins (2006) describes, is like passive vocabulary. It can only be used when it is activated, i. e. specifically addressed. A student may possess many pieces of such knowledge, but would not be able to apply it without a specific reminder and thus could rarely use it to form new understanding.

Tacit Knowledge is knowledge that instructors, i. e. experts, possess without being aware of it. Hence, it can be seen as the instructor's version of inert knowledge. Like a student who is not able to use their inert knowledge without being reminded of it, the expert will not explain and thus make explicit their tacit knowledge without being prompted to do so – even though they might use their tacit knowledge frequently. Students will often still absorb their instructors' tacit knowledge by simple imitation. Like the instructor, they will not be aware of this knowledge. Typical examples of tacit knowledge in engineering are forms of notation and the approaches used to solve problems.

For further descriptions of these different kinds of troublesome knowledge in the engineering context, the reader is referred to Male and Baillie (2014).

10.1.3 *Liminality and Mimicry*

Meyer and Land (2003) suggested that in the process of learning a threshold concept, students often are in "a suspended state in which understanding approximates to a kind of mimicry or lack of authenticity." This suspended state is called the *liminal space*. "It is an unstable space in which the learner may oscillate between old and emergent understandings just as adolescents often move between adult-like and child-like responses [...]. But once a learner enters this liminal space, she is engaged with the project of mastery unlike the learner who remains in a state of pre-liminality in which understandings are at best vague" (Cousin, 2006).

Meyer and Land (2006) suggest that students notice they are stuck and use mimicry to compensate. Such mimicry can frequently be observed with students who start to use technical terms in ways that make it obvious they have not correctly understood them.

10.1.4 *Methods in Threshold Concept Research*

The methods used in the research of threshold concepts can be divided into two categories: methods for identifying *potential* threshold concepts and methods to investigate whether a possible threshold concept actually meets the criteria of a threshold concept.

10.1.4.1 *Identifying Possible Threshold Concepts*

By far the most common approach to identify possible threshold concepts seems to be the use of focus groups and interviews in general. In these, students or instructors are first introduced to the idea of threshold concepts. Then, they are asked which concepts seem particularly transformative or troublesome to them (e. g. Scott et al., 2012; Male and Baillie, 2014).

However, Shinners-Kennedy and Fincher (2013) note that "regardless of whether the method used was interviews, structured tasks or questionaries almost every study that has asked learners to look back and recall a time when they had a conceptual difficulty that had been restored, and to recount how it had been resolved, has been unable to accumulate empirical evidence that supports the identification of a particular concept as a threshold concept."

As an alternative to interviews, Scott et al. (2012) suggested to use histograms of test scores as a quantitative method to identify threshold concepts. If a test would only cover one concept, a bimodal distribution of scores in that test would indicate that concept to be a threshold concept. Their reasoning is that students can either *have* or *have not* understood that concept. There should be no in-between. However, in later studies Scott et al. did not mention this method again and instead used qualitative means and introspection to identify threshold concepts.

10.1.4.2 *Testing the Characteristics of a Concepts*

Several different methods have been proposed to test if a concept possesses the defining characteristics of a threshold concept.

Scott and Harlow (2012) discussed the feasibility of measuring the irreversibility of a concept. A longitudinal study could be used, which required the collection of data over a very long time frame, making it unpractical. Alternatively, older subjects could be investigated. With this approach, however, it is difficult to determine if the test subjects had understood the concept in the past.

Scott and Harlow (2012) used interviews to test the irreversibility of several concepts they proposed to be threshold concepts (see Section 10.2). The subjects they interviewed had retired or changed fields at least 5 years prior. Scott and Harlow reported: "The results have been fascinating. Subjects often claimed to fully understand a concept, but then surprised us and themselves by not being able to describe it to us. Some eventually exposed themselves as having never really understood the idea. To date we have seen no evidence that our threshold concepts are any more irreversible than other concepts."

It is also commonly suggested to measure the difficulty of a concept as an indicator for it being troublesome. Such a measurement has to be made at the correct point in time, i. e. when students would have understood a non-threshold concept but not a threshold concept. Identifying a concept this way, however, does not prove the concept to be a threshold concept, but just a possible threshold concept. "If a concept relies upon an earlier idea, lack of understanding of that earlier idea alone can result in trouble learning the new idea" (Scott and Harlow, 2012).

In the author's opinion, *troublesome* must be distinguished from *difficult*. A concept is troublesome when there are obstacles for the learner that counteract their attempts to understand the concept. Being troublesome, thus, is an internal property of a concept that cannot be observed directly. A troublesome concept often also is difficult. A concept is difficult when many students make mistakes or fail trying to use it. Being difficult is an external property of a concept that can be observed using tests. However, being troublesome is not the only factor that can make a concept difficult. The concept could for example have been explained poorly or students had focused on other concepts that they felt were more troublesome. Simply analyzing tests for the most difficult questions therefore can help to identify concepts that are potentially troublesome, but cannot be used to determine if a concept actually is troublesome.

Meyer, one of the founders of threshold concept theory, claimed in personal communication with Scott and Harlow (2012) that "concepts do not present in a continuum, but fall all-or-nothing into being 'threshold' or not". Consequently, attempts in identifying threshold concepts should result in clear decisions. However, Shinners-Kennedy (2016) observes: "For the most part, the strategies deployed by researchers to-date have yielded tentative proposals only and the uncertain nature of the outcomes has been a frustrating experience for investigators."

The alternative approach, employed by for example Scott and Harlow (2012), is introspection and careful reasoning based on the researchers' expert knowledge of the subject. This approach is also employed in the remainder of this chapter.

10.1.5 *Criticism of Threshold Concepts*

Rowbottom (2007) heavily criticized threshold concepts for their fuzzy definition. He for example quoted Meyer and Land (2003) stating that a "threshold concept [...] is likely to be [...] possibly often (though not necessarily always) bounded". While the author of this thesis would also prefer a more concise definition, he does not support this criticism. The ellipsis in that quote is from the first paper on threshold concepts and spans more than one page. In the author's opinion, many of these repetitious constraints actually increase readability, as they otherwise might have been forgotten.

Threshold concepts are claimed to exist in every subject imaginable. Thus, threshold concepts are used and described by researchers from diverse fields. Consequently, explanations of threshold concepts theory are written by and for researchers from all of these fields, including the sciences, humanities, economics, etc. While a scientist surely is surprised to find that Meyer and Land (2003) use the biblical story of Adam and Eve to illustrate irreversibility, such an explanation might be ideal for a theologian. It is no surprise that not all descriptions of threshold concepts are helpful for researchers from the sciences or engineering, who would likely prefer a *definition* that can easily be operationalized. There also are no agreed-upon examples that can be used to illustrate what a threshold concept is. However, such examples would likely not be understood by the majority of readers, who statistically speaking are unlikely to be experts in the fields such examples would come from.

Rowbottom (2007) also criticizes that the transformation caused by a threshold concept is strongly dependent on previously learned subjects. However, many of the theories used in educational research, like the ones introduced in Chapter 2, respect or even emphasize the differences between learners. Virtually nothing in education is true for every student. The goal of threshold concept theory is not to identify concepts that are transformative for everyone, but to identify concepts that can *generally* be treated as transformative for students.

10.1.6 *What are Threshold Concepts Good for?*

The prior sections described several difficulties in identifying threshold concepts and the dissatisfaction of at least some researchers due to their fuzzy definition. Therefore, one might ask, what threshold concepts actually are good for. In the author's opinion, the value of threshold concept theory in education is not to irrefutably prove that a concept is or is not a threshold concept, but to frame the discussion of what should be taught in the limited time available in a course.

For this discussion, the concepts students encounter in a course can be divided into three categories:

1. *threshold concepts* as described above, which Land et al. (2005) call the "Jewels in the curriculum", but also

2. *core concepts* that are the "building blocks" on which other concepts are build. They have to be understood for a student to

proceed, but do not lead to a different view of subject matter (Meyer and Land, 2003) and finally

3. *supplemental concepts* that present handy tools in practice or are part of an expert's way of thinking and behaving.

These different categories of concepts can be illustrated using examples from a course in electrical engineering. The existence of the quantity voltage and its unit volt are core concepts in electrical engineering, as they are required for countless other concepts. In this chapter, it will be argued that the electric potential is a threshold concept. The node-voltage analysis, a standardized approach for calculating all currents and voltages in a circuit, is an example for a supplemental concept.

Core concepts obviously have to be included in the curriculum before other concepts that depend on them are introduced. Threshold concepts should be included in the curriculum due to their strong effect on students. While they are often troublesome and thus require more attention than core concepts, they also are transformative, integrative, bounded, and irreversible, resulting in long lasting effects on the learner and their understanding of the subject. Each of these five characteristics is an argument to build instruction around threshold concepts, thereby ensuring that students have enough time to pass the liminal space and gain the benefits of having understood a threshold concept. Supplemental concepts are optional, but often can still be included in the curriculum successfully. They can for example be incorporated into exercises or be shown as part of an example when discussing a threshold or core concept.

10.2 PROPOSED THRESHOLD CONCEPTS IN ELECTRICAL ENGINEERING

Several researchers have investigated threshold concepts in electrical engineering. Flanagan (2019) provides a list of papers published on threshold concepts in different fields. Reeping et al. (2017) provides a summary of concepts in electrical engineering that have been proposed to be threshold concepts or at least troublesome.

Carstensen and Bernhard investigated student learning of the Laplace transform in the context of analog circuitry. They do not mention any specific threshold concepts, but they identified what they called *key concepts*, concepts that "open up the portal of understanding" (Carstensen and Bernhard, 2008) by helping students to make links between different concepts. When investigating a specific lab, they conclude that the "key concept [in this lab] is the palette of possible solutions" to the problems given (Carstensen and Bernhard, 2016).

For several years Scott and Harlow (2012) have been researching threshold concepts in electronics, with the goal to develop an electronics concept inventory based on these threshold concepts. As part of their research, they compiled a list of possible threshold concepts in electronics:

- *Circuit modeling*, usually first encountered by students in the context of *Thévenin's theorem*,
- *linear approximation* of e. g. *dynamic resistances*,
- *phasors* as complex electrical quantities, encountered for example in the context of *reactive power*,
- *feedback*, most simply seen with *operational amplifiers*, and
- *dependent sources* or in general the dependence of one quantity on the value of another, what they call *transdependence*.

Each of these threshold concepts is a combination of a general or abstract concept and a specific concept. The specific concept is the first occurrence of the general concept in a typical electrical engineering course. Scott and Harlow (2012) do not specify whether they consider only one of the two to be a threshold concept or if they consider the threshold concept to be the combination of both the specific and abstract concept. However, in a different paper, Scott et al. (2012) express their "high level of confidence" in their identification of the five threshold concepts.

Carnes (2016) investigated students' mental models of threshold concepts in electrical engineering. Based on Meyer and Land's analogy of threshold concepts acting like portals of understanding (e. g. Meyer and Land, 2003), he states: "In electrical studies, the concepts of voltage and current represent one of these portals. The representation of nearly every concept in electrical phenomena has at its base the movement of charge, which is expressed by the concepts of voltage and current. These must be understood to be able to predict and to control nearly all electrical phenomena" (p. 9). While the author of this thesis values Carnes' observations on student understanding, he does not agree with Carnes' assessment that current and voltage are threshold concepts. It certainly is true that current and voltage are *integrative*. They are linked to almost every other concept in electrical engineering. However, Carnes does not comment on the other properties of threshold concepts. Based on his shortened argument, every core concept would be a threshold concept. However, in the author's opinion, a threshold concept has characteristics that a core concept does not have, most importantly being transformative. The following two sections will describe why in the author's opinion *current flow* and the *electric potential* are threshold concepts in circuit analysis. As will be discussed later, *current* and *voltage* would then only be core concepts.

10.3 Current flow as a threshold concept in dc circuit analysis

Current flow was first suggested to be a threshold concept by Scott and Harlow (2012). They described it under the name of *holistic current flow* as

> "the physical appreciation that current is charge movement per unit time, that charge is conserved in a conductor, and that, as far as low-frequency electronic circuits are concerned, force of current is conveyed instantly throughout a conductor. [...] Current flows 'incompressibly' through conductors". (Scott and Harlow, 2012)

As with the Fourier transform discussed before, the threshold concept of current flow is the understanding how current behaves, not the mathematical equation that describes its behavior. As Scott and Harlow (2012) state, Kirchhoff's laws are *not* threshold concepts, but just "tools for attaching quantitative equations to ideas of current flow".

While Scott and Harlow (2012) first described the concept of current flow in the context of threshold concepts, they did not discuss it as such in detail. The remainder of this section will discuss the defining characteristics of threshold concepts in respect to the concept of current flow.

Troublesome

Being troublesome is not a criterium that concepts *must* fulfill to be considered a threshold concept. Still, it is useful to begin an analysis of a threshold concept with this characteristic. Troublesome aspects of a concept might reveal ways in which the concept transforms students' understanding or integrates with other concepts.

The concept of current flow might seem trivial to many experts and even students, considering that Kirchhoff's Current Law (KCL) is one of the most basic concepts in electrical engineering. However, as reported in Chapter 7, several aspects of this concept present difficulties for students. Two relevant examples discussed in that chapter are the misconception that current is "used up" and the misconception that the source currents of current sources in series add up.

In German speaking countries, one possible origin of the misconception of current being "used up" (p. 113) is the common usage of that phrase in every-day language. The author's electricity bill, for example, contains the word "Stromverbrauch", i. e. "used-up current". Thus, the misconception might be caused by *troublesome language*. The idea that something must be consumed in order to deliver power to a load could also be a contributing factor. Without having understood the concepts of power and voltage (or rather the electric potential, as discussed below) the idea that current is not consumed in loads could be a form of *alien knowledge*.

The misconception that the source currents of current sources in series add up (p. 133) could be caused by the misconception that sources increase the current through them (see p. 133). To students it seems sources must "add something" to the circuit. A source, after all, "generates something". The idea that sources "only" define the current through or voltage across them might be a case of *alien knowledge*. This alien knowledge, in turn, might trigger the misconception that the source currents of current sources in series add up.

Based on the observation of these misconceptions, current flow should be considered conceptually difficult, because aspects of it represent troublesome language and alien knowledge. Furthermore, the concept itself can be considered the result of *conceptually difficult knowledge* due to it being almost never experienced in every-day life. Certainly, incompressible flow such as that of current does occur in nature. A prominent example for such a flow are systems of closed pipes. However, the examples of flowing media that are observed most often do not behave the same way. The level of water flowing down a river can decrease and increase with the water eventually flowing over the river's edges. Traffic "flowing" along streets can "compress or decompress" when the cars move closer together or farther apart.

These differences between the flow of current and other kinds of flow used in different analogies present *troublesome language*. Carnes (2016) reported that "all of the students in [his] study used analogies in one form or another to describe their thinking. [...] Not surprisingly, the most common analogy used was the water flow analogy with several variations. Of the fifteen participates, eleven of them talked about water flow in waterfalls, rivers, pipes, and even a bucket brigade" (p. 83). Many of the analogies mentioned by Carnes will break down when taken too far. For students who have already passed the threshold and understand current as a flow in the sense of physics, these differences often do not present a problem. For students who have not passed this threshold, however, reliance on such analogies might pose a problem.

Transformative

Understanding the concept of current flow as described above can be highly transformative for students. Like most aspects of electrical engineering, current cannot be observed directly. Thus, everything a student knows about the behavior of current is derived from verbal descriptions, mathematical equations like KCL, etc. It can be difficult to derive an understanding of the concept from these. Especially a too strong focus on mathematical equations can be detrimental with students becoming able to apply the equations like KCL, but still not acquiring an understanding of the concepts.

The author remembers that when he started his studies in electrical engineering, he spent much of the first semester searching for good descriptions of how current and voltage behaved in a circuit and even inside circuit elements. In retrospect, such a description would essentially be the concept of current flow and the electric potential (discussed below). However, despite several trips to the library, the author never found a description that satisfied him. All that he could find were explanations that boiled down to the mathematical equations of KCL and Kirchhoff's Voltage Law (KVL). Due to increasing familiarity, the mathematical formalism of Kirchhoff's and Ohm's Laws slowly formed a sort of understanding for the author. The sought after qualitative understanding, however, was only reached years later.

While such a personal anecdote is hard to generalize, the research by Carnes (2016) seems to suggest a general pattern. Students in his study "claimed that they had only touched on [conceptual understanding] briefly before moving into the use of mathematical equations. So it is not too surprising that for five of the fifteen participants, mathematical equations were their primary means of addressing electrical phenomena" (p. 94). Carnes lists several explanations. One student described that "the differential equations are more real to her than the physical phenomena" and another student "prefers to think in terms of the calculations that need to be done" (both p. 87). Another student described their inability to imagine current flow: "I know how to calculate current flow, but it doesn't seem too intuitive to me how this electron knows, how it knows what to do... It just seems to know everything before it starts running... It's magical" (p. 84).

Instruction that focused on the concept of current flow could possibly have created the kind of eureka moment that the author, and likely the students quoted above, lacked.

Understanding the concept of current flow also provides the ability to envision the flow of current in a circuit, an ability often used by electrical engineers. It should be noted that students with an incorrect understanding of current flow also use this ability, albeit incorrectly.

Integrative

The concept of *current flow* is integrative in that it connects with several other concepts on the *same level*. Particularly strong relations exist to the concept of the current divider, whose behavior is a direct consequence of current flow, Ohm's Law and KVL.

The concept of power is also closely connected to current flow, not only as the mathematical product of current and voltage. Many students who use the water analogy seem to base their understanding on the "sink" model, where "the electrons enter the wire at the battery and then flow to the load where they are consumed" (Carnes, 2016, p. 93). It seems likely that the idea of electrons (or current) being consumed is born out of the logical necessity of "something" being "consumed" at the load. It might be necessary for students to understand the concept of power to be able to understand current flow.

Bounded

While the current flow is a subject-specific version of the general concept of flow, it is usually not introduced as such in circuit analysis. Thus, for most engineering students, it is a new concept.

The concept of current flow only applies when charges are not stored, added, or removed at any place in the circuit. This condition is for example broken when capacitors are considered, where the current seemingly ends on the plate of the capacitor. Only the displacement current, which likely is another threshold concept, can "fix" this problem.

Irreversible

Like many other threshold concepts, the current flow is a very simple concept, in the sense that it does not require complex mathematics or a lot of additional knowledge to be understood. The troublesome aspects seem to all originate from it having no observable real-world equivalent. Thus, once understood it is likely to never be forgotten.

Additionally, it is a foundational concept in the field of electrical engineering and used on a daily basis by electrical engineers. It can, therefore, practically not be forgotten. Scott and Harlow (2012) suggest that threshold concepts "are no more readily remembered than other ideas, but they are frequently used in a subject's routine thinking, so transformed is the subject by the immersion in his or her discipline, that the memory is 'dynamically refreshed', in the manner of DRAM".

10.4 THE ELECTRIC POTENTIAL AS A THRESHOLD CONCEPT IN DC CIRCUIT ANALYSIS

There is a large number of dual concepts in electrical engineering. While not true in the strict sense, in a practical sense the *electric potential* is the dual concept to *current flow*. The concept of current flow describes how current behaves in a circuit. The concept of the electric potential does the same for voltage.

In this context of threshold concepts and in analogy to the description by Scott and Harlow (2012), the concept of the *electric potential* encompasses the appreciation that in DC circuits a real-valued electric potential exists, which has the unit of volt, or energy per unit charge. The value of this potential is defined for every point on a wire. Potential differences are voltages, with the unit of volt, or work per unit charge.

As with the concepts of the Fourier transform and current flow, the threshold concept is not the mathematical relation between the electric potential and voltage, but the idea of the electric potential. This section will show that the electric potential is a threshold concept "opening up a new and previously inaccessible way of thinking about" (Meyer and Land, 2003) voltage. Each subsection will address one of the defining characteristics of a threshold concept.

Troublesome

As discussed before, being troublesome is not a characteristic a concept *must* fulfill in order to be considered a threshold concept. Still, it is worth to discuss the ways in which a concept is troublesome for students, as these can indicate how that concept is transformative or integrates with other concepts.

Compared to other concepts in electrical engineering, the concept of the electric potential might not be that troublesome for students. Still, like most concepts in electrical engineering, the electric potential is *conceptually difficult knowledge*, as no directly observable equivalent exists in the real world. Thus, students must build their mental models solely on verbal descriptions and mathematical equations and cannot use direct observations to form the model. However, the electric potential is similar to the concept of potential gravitational energy. Students can observe potential gravitational energy by lifting up objects of different weights to different heights or observing objects fall or roll down.

As described in the next section, the electric potential is transformative in that it "opens up a portal" for students to understand voltage. Because of this relation between voltage and the electric potential, it is also instructive to discuss the ways in which the concept of voltage can be troublesome for students.

Like the electric potential, voltage must also be considered *conceptually difficult knowledge*, as it too has no directly observable real-world equivalent. As with the electric potential, students must build their mental model of it solely on verbal descriptions and mathematical equations and cannot use direct observations to form the model. However, there are several arguments that can be made for why voltage might be more troublesome for students than the electric potential.

First of all, voltage can also be considered *conceptually difficult knowledge* due to the many misconceptions associated with it. Certainly, voltage and KVL may seem trivial to experts and even students, as they are among the most basic concepts in electrical engineering. Still, several examples in Chapter 7 have shown students incorrectly understanding voltage. About half of all students in a large study for example believed that there is no voltage across an open switch or circuit (Section 7.4.3). Students also failed to recognize that an ideal voltage source maintains a constant voltage across it (Section 7.1.3). These misconceptions seem be related to the concept of voltage (or potential difference) that is measured between two points, but not necessarily to the concept of the electric potential as a value at one point. This difference might indicate that voltage could be more troublesome for students than the electric potential. However, it might be that the electric potential has similar misconceptions associated with it, that simply are less well researched.

Secondly, voltage is a quantity defined between two points, whereas the electric potential is defined at only one point. Relative to the electric potential, voltage therefore presumably is more complex and subsequently difficult to understand. This difference in their difficulty might be similar to the difference in difficulty between position and speed. Some students in interviews by Trowbridge and McDermott (1980) were able to adequately define speed, but still mistakenly assumed an object in front of another one to be faster, regardless of their actual speed. These observations show a preference for the value that is based on only the object's position and not on the difference between its position at two points in time.

Thirdly, the distribution of voltage, mathematically described by KVL, likely also presents conceptually difficult knowledge. As shown in Section 9.4.4, the loop rule is quite a complex law as several independent aspects have to be considered. A closed loop has to be found, its direction has to be defined, and the directions of the individual voltages have to be compared to the direction of the loop. This complexity does not exist with the electric potential. It seems unlikely that students are familiar with other similar laws of nature, or conservative force fields in general. Thus, they likely have no experience with such laws when learning about voltage. Based on Chi's theory of orthogonal categories, this situation might be a case of a missing schema. Students are unfamiliar with conservative force fields and thus had trouble understanding voltage.

The theory of orthogonal categories was introduced in Section 2.3.2.3 (p. 19).

Additionally, in some cases, troublesome language can also affect student understanding of voltage. As described in Chapter 9, the term 'voltage' is not used in the sense of a potential difference, but also as voltage at a point, i. e. as a synonym for the electric potential. While this double meaning might not be problematic for experts, who can determine the use of the term from context, it likely can be an obstacle for students, who might not have become aware that there are two distinct uses of the word.

Transformative

As described above, voltage is conceptually difficult knowledge and therefore troublesome for students, as there is no observable equivalent in the real world. While the electric potential also is conceptually difficult knowledge, it seems to be less difficult than the concept of voltage, having at least similarities to observable concepts. Therefore, the electric potential provides a path to understanding voltages, as potentials in general are known or can be related to real-world examples.

As reported in Section 7.4.4, "the voltage concept is one of the most abstract concepts introduced in the secondary-school physics course. Usually students do not develop an independent voltage concept, but interrelate it to the concept of electric current" (von Rhöneck, 2008). This observation seems to also apply to at least some engineering students. As described in Section 7.4.4, one student for example argued that voltage is the speed and current the number of electrons through a wire. Other students believe that voltage is a substance that moves through the wires (p. 152). In this mental model, voltage might be independent of current in its value. In its behavior, however, is is similar to current.

A mental model of the electric potential surely presents a foundation on which to build a mental model of voltage. That mental model could then be independent of the mental model of current, except for relations like Ohm's Law and the concept of power. As such a mental model of voltage would depend on the electric potential, it needed to be adapted for the context of AC circuits and especially for the case of induced voltages. Crucially, such a mental model of voltage contains the main difference between current and voltage, with current being something that flows and can be measured at one point in the circuit and voltage being something that *is* between two points in the circuit.

While there certainly are other ways for students to build mental models of voltage that are not dependent on current, the electric potential seems to be the most obvious and easy path. Understanding the electric potential will "open[...] up a new and previously inaccessible way of thinking about" (Meyer and Land, 2003) voltage.

As shown in Section 9.4.2, the potentials in a circuit also highlight the connectedness of the circuit elements. Thinking about the electric potential allows students to better imagine the distribution of voltages in a circuit.

Integrative

The concept of the electric potential integrates with the concept of voltage as voltages are potential differences. In addition, the electric potential is used in other contexts in electrical engineering, such as the node voltage analysis. Even the textbooks shown in Section 9.3.1 that did not use the electric potential used an equivalent concept (voltage at a point) when discussing node voltage analysis.

Bounded

The abstract concept of a potential exists outside of electrical engineering. The electric potential, however, is not necessarily introduced as a specific form of this abstract potential. Thus, for many students, especially in electrical engineering, the electric potential is likely independent of the abstract concept of potential.

The electric potential therefore can be considered strongly bounded. When limited to real values, it only applies to DC circuits. The concept can be extended to AC circuits, using complex numbers. This extension, however, likely looses some explanatory power for many students. Once changing magnetic fields occur, i. e. voltages are being induced, no scalar potential exists anymore.

Irreversible

Like *current flow*, the *electric potential* should be considered irreversible for two reasons. Firstly, it is a fundamental concept that does not rely on any complex mathematics or other concepts, making it less likely to be forgotten. Secondly, it is used on a daily basis by electrical engineers.

10.5 CONCLUSION

Based on the observations gathered above, *current flow* and the *electric potential* should be considered threshold concepts. Understanding these two concepts "open[s] up a new and previously inaccessible way of thinking about" (Meyer and Land, 2003) the nature of current and voltage and allows students to differentiate between these two concepts.

Teaching current and voltage without the proper care to ensure students understand the threshold concepts current flow and electric potential might still enable students to become competent in quantitative questions solved using KCL and KVL. However, based on the observations presented in this thesis, it is not unlikely that these students might hold fundamental misconceptions after instruction that could influence their decisions at critical moments.

Due to the nature of threshold concepts, it would, however, not be enough to simply lecture about *current flow* and the *electric potential*. Threshold concepts are troublesome for students and often require them to pass through a phase of liminality. To pass this phase, they must be supported in an active learning environment. Investing the time to help students pass through this liminal space is worthwhile. The invested time will ensure that students can thoroughly probe their understanding of these critical concepts and are ready to encounter new thresholds that they would possibly not be able to pass without a solid understanding of the basic concepts discussed here.

11 SUMMARY & CONCLUSIONS

Chapter 1 introduced three main research questions, which will be answered in the next section. Artifacts from this project that can be used in instruction and other research projects, as well as the limitations of this study and possible future work will also be discussed in this chapter.

As this thesis is the first German dissertation on university-level electrical engineering education research, it contains detailed descriptions of the different explanatory frameworks and theories it uses as well as its methodology. This detailed background is not only included as a resource for the reader, but more importantly to help researchers familiar with educational research understand the similarities and differences between this study and discipline-based educational research conducted in Germany and internationally. The background information provided in this thesis can thereby help to describe the influences that affect the research conducted by the Engineering Education Research Group (EERG) at Hamburg University of Technology[1] (TUHH).

Chapter 2 introduced several theoretical frameworks that are relevant for this thesis. Most importantly, several theories of conceptual change were presented. These theories all rely on the idea that the mistakes that students make are not the results of random errors, but the consequences of flawed mental models. The different theories diverge in their assumptions about the nature of these mental models. Some theories for example assume these models to be similar to formal scientific models, while others see them as connections of atomic statements. The core idea of all of these theories, however, is that changing these mental models is not easy and requires active work by the students. The study of student misconceptions, which were also introduced in Chapter 2, is one branch of educational research that originates from these theories. The chapter also introduced Tutorials as an established method for addressing such misconceptions. They are discussed in many parts of this thesis.

Chapter 2 also presented Decoding the Disciplines (DtD) and APOS-Theory, two explanatory frameworks that offer unique methods for education research. DtD provides a method to uncover an experts' understanding of particularly difficult concepts and methods while APOS-Theory offers explanations and methods for determining the

1 "Technische Universität Hamburg" in German, formerly "Technische Universität Hamburg-Harburg".

internal relations and dependencies of different concepts within a discipline.

Chapter 3 provided an overview of the research that preceded this thesis. Many studies since the late 1970s have investigated student understanding of concepts related to circuit analysis. However, most of that research was conducted in secondary schools or in the context of physics courses. Only in the last 20 years research has expanded to specifically investigate engineering students' understanding of basic circuit concepts and to cover concepts that are specific to electrical engineering.

This thesis contributes to that expansion by investigating the conceptual understanding of students in several engineering courses, which are described in Chapter 4. Its main focus lies on the course EE1ME, an introductory electrical engineering course at TUHH that is attended by students who do not major in electrical engineering. Most of these students study mechanical engineering. Additional data was collected in electrical engineering courses for electrical engineers as well as a course at Loughborough University in the UK.

Chapter 5 described the research approach taken to investigate the understanding of these students. The mixed-methods approach combines qualitative and quantitative methods. Qualitative research methods were used to better understand students' beliefs and reasonings and quantitive research methods were used to determine the frequency of different answers and explanations. Put together, these methods allow to judge the frequency of certain beliefs and misconceptions.

Two research methods were developed (further) as part of this thesis and discussed in more detail in Chapter 6. As part of this research project, a self-generated identification code (SGIC) was developed for the use by the EERG at TUHH. This identification code was used in later parts of this study to distinguish students who had and who had not participated in an intervention and to determine how individual students' answers changed over time. In addition, an algorithm for the automatic evaluation of ranking questions was developed and used throughout this research project. Both research methods are discussed in Section 11.2.

Chapter 7 is the first of three chapters that discusses specific data on students' understanding and learning. It investigated students' understanding of different concepts in circuit analysis from multiple perspectives. Seemingly simple test setups, like the five-bulbs test (see Section 7.1), the parallel connection of voltage sources and series connection of current sources (Section 7.3), open circuits (Section 7.4), and short circuits (Section 7.6) revealed many student difficulties. It might seem problematic that many students were not able to correctly answer questions about such "trivial" circuits while they are supposed to learn how to calculate networks with a significantly higher complexity. However, these difficulties align well with prior research and show that the most critical aspect to student learning is the understanding of fundamental concepts. Students had difficulties with these simple setups because these tests were designed to reveal flaws in their mental models. As described above, mental models cannot be changed easily and thus are often unaffected by traditional instruction.

While Chapter 7 mostly documents students' difficulties and misconceptions, the data presented in that chapter has a positive side. The incorrect answers reported in that chapter are often consistent, i. e. they follow some logic, even when they rely on an incorrect assumption. Understanding these misconceptions provides a path for educators to address them. Specifically addressing common misconceptions by helping students recognize them has been shown to be a successful approach in instruction. In Chapter 7 it could for example be shown that Tutorials are effective in reducing the misconceptions they were designed to address.

Chapter 8 presented a detailed analysis and revision of the first two Tutorials in circuit analysis: *Current and Resistance* and *Voltage*. The Tutorials were analyzed by uncovering the Intended Observations and Inferences (IOaI) of the Tutorials, a process similar to parts of the research cycle in DtD. Through this process, it was found that the Tutorials, materials developed by experienced educational researchers that had been evaluated extensively, still contained tacit knowledge. The Tutorial *Current and Resistance* for example introduced current as a 'flow', but did not specify the properties of a flow. The Tutorials are among the artifacts produced in this research project (see Section 11.2).

One of the observations reported in Chapter 7 was that students had more difficulties with concepts related to voltage than with concepts related to current. One of the most problematic concepts was found to be the voltage across an open switch or open circuit, which about half of all students believed to always be zero. Chapter 9 explored the use of the electric potential as a tool for helping students overcome their misconceptions related to Kirchhoff's Voltage Law (KVL), specifically the voltage across an open switch. Different approaches in textbooks are compared in the chapter and using a mathematical description of circuit analysis, the hidden difficulties of KVL were shown. After a brief analysis of prior worksheets that used the electric potential, the development of a new Tutorial called *Potential* was documented. Using a pre-post-test analysis it was found that the Tutorial helped students overcome their difficulties with the voltage across open switches.

Chapter 10 introduced threshold concept theory, which is unlike the other explanatory frameworks introduced in Chapter 2 in that it has no quantitative component. A threshold concept is defined by several criteria, most importantly by transforming students' understanding of subject mater or even their view of the world when they are learned. While the lack of an operationalization makes it difficult to determine if a concept actually is a threshold concept, the theory is powerful in that it helps to structure the always necessary discussion of which concepts should be included in a curriculum and which should be left out. In this chapter, it was argued that both the concepts of current flow and the electric potential are threshold concepts, making their inclusion in the curriculum very valuable.

11.1 ANSWERS TO RESEARCH QUESTIONS

Chapters 7 to 9 presented many pieces of data on student understanding and learning of circuit analysis. In this section, conclusions are drawn from this data, providing answers to the research questions.

As these answers condense many different observations into a few lines of text, they inevitably are very abstract. While the author considers them important, he sees the main contribution of this work not in the condensed information presented below, but in the detailed documentation of individual student difficulties and misconceptions provided throughout this work. Understanding student difficulties and misconceptions can enable educators to better understand and support their students. Readers who have started reading this thesis with the current chapter are therefore encouraged to also study the previous chapters.

11.1.1 *Research Question RQ 1: What are engineering students' conceptual difficulties with current and voltage?*

As part of this research project, several misconceptions were identified among engineering students. They are listed in Table 11.1.

Many of these misconceptions had previously been identified by other researchers, most notably McDermott and Shaffer (1992), who had investigated students in physics courses in the USA. Based on the observations presented in this thesis, it seems that engineering students in principal hold the same misconceptions as students at other universities and in other study programs. However, data suggests that the frequency of certain misconceptions depends on the student population and their course of study. The misconception of current being "used up", for example, occurred less frequently among the engineering students. Furthermore, the misconception presented differently, as the engineering students almost never used the phrase "used up", but other phrases such as a bulbs receiving "less juice". Other misconceptions, like the belief that there always is zero voltage

Table 11.1: Misconceptions observed among engineering students as part of this thesis.

Misconception	Page
The direction of current and order of elements matters	p. 112
Current is "used up"	p. 113
Failure to distinguish between voltage and potential	p. 113
Failure to recognize that an ideal battery maintains a constant voltage between its terminals	p. 114
Batteries behave like ideal current sources	p. 114
Current and voltage can be considered independently	p. 114
Tendency to reason sequentially and locally, rather than holistically (1 of 2)	p. 115
Failure to recognize that a voltage source maintains a constant voltage between its terminals	p. 120
Source voltages of voltage sources in parallel add up	p. 131
Source currents of current sources in series add up	p. 133
Sources increase the current through or voltage across them	p. 133
Voltage is a property of current	p. 150
Voltage is caused by current, *or* voltage and current always appear together	p. 152
Voltage is a substance that moves through the circuit	p. 152
Ohm's law applies to open circuits	p. 153
Tendency to reason sequentially and locally, rather than holistically (2 of 2)	p. 170
Current splits evenly at each node	p. 171
Short circuits have no effect	p. 171
KCL applies to the currents of circuit elements, not branches connected to the node.	p. 200

across an open switch, seem to occur more often among the engineering students than in other populations.

Some of the misconceptions listed in Table 11.1 had previously not been reported, like the *failure to recognize that a voltage source maintains a constant voltage between its terminals*. However, the author would suggest that these misconceptions are not specific to engineering students. The concepts that they relate to simply are used less frequently in non-engineering courses.

11.1.2 Research Question RQ 2: *To what extent can the conceptual difficulties identified before be overcome through the use of existing Tutorial worksheets?*

The research on RQ 2 focused on the Tutorials *Current and Resistance* and *Voltage*, which are designed to be the first two Tutorials students work on regarding the subject of circuit analysis. As shown in Chapter 7, the Tutorial successfully reduced students' difficulties with the concepts tested by the five-bulbs test, like the belief that current is "used up". Other misconceptions, like the ones that cause students to believe that there is no voltage across open switches, were still common after the Tutorials.

Based on these observations, it seems likely that the Tutorials had the same effect on the engineering students investigated in this study, as the y had on the students in many other courses. Not surprisingly, the effect of the Tutorials was limited to those concepts that the Tutorials were designed to address.

11.1.3 Research Question RQ 3: *To what extent can an improved understanding of the concept of electric potential help students overcome specific conceptual difficulties with voltage?*

The voltage across an open switch or circuit was found to be a critical test for students' understanding of KVL. Of more than 5500 students on whom data was gathered, 52% incorrectly believed the voltage across an open switch to be zero. This false belief was found to be common in many different cohorts. In 16 of the 18 cohorts investigated, the false belief was held by more than ⅓ of the students. In 3 cohorts, it was held by more than ⅔ of the students.

The Tutorial *Potential* was found to help reduce the frequency of this misconception. Among the students tested, the frequency of this belief decreased from 64% to 33% (instructor A), from 64% to 19% (instructor B), and from 65% to 25% (instructor C), when comparing the pre-test integrated into the Tutorial and the respective post-test. While some control groups also showed strong improvements, in most cases there was a clear difference between the control and the intervention group.

Apart form this specific application of electric potential in the Tutorial, Chapter 10 showed that the electric potential should be considered a threshold concept in DC circuit analysis. It provides a path for students to form an understanding of voltage that is independent of their understanding of current and should therefore be included in circuit analysis curriculums.

11.2 ARTIFACTS USABLE IN ELECTRICAL ENGINEERING EDUCATION AND ENGINEERING EDUCATION RESEARCH

As part of this research project, several artifacts were produced that can be used in future engineering education research projects and in electrical engineering education.

Algorithm for Matching SGICs and Collision Probabilities

In order to identify tests that were answered by the same student, SGICs were introduced in Section 6.1. An algorithm to find matching SGICs was developed and is documented in that section. This algorithm can be used in future projects. It likely is similar to the matching algorithms used by other researchers. However, as the specific algorithms are rarely documented in publications on SGICs, that assumption cannot be verified.

In addition, the collision probabilities tabled in Table 6.1 can be used as a basis for the development of SGICs elsewhere. The data aligns well with similar measurements by Schnell et al. (2010).

Algorithm for the Evaluation of Ranking Tasks

This thesis relied on ranking questions. This type of question was introduced in Section 5.3.4. In these questions, students were asked to rank several quantities by a common measure using relational operators. Students would for example rank the bulbs in the five-bulbs test (Figure 6.6) as A=D=E>B=C. As part of this thesis, an algorithm was developed to automatically evaluate such rankings, extract specific relations, and test them for inconsistencies. As the algorithm translates the rankings into a graph, the evaluation can be performed using common algorithms from graph theory, for which existing and optimized libraries can be used. In addition to its use in research, as in this thesis, the algorithm could be used for automated online assessments, allowing instructors to add this valuable type of qualitative questions to their tests. The algorithm is documented in Section 6.2.

Revision of the Tutorial Current and Resistance and the Tutorial Voltage

As part of this thesis, the Tutorial worksheets *Current and Resistance* and *Voltage* (originally published in McDermott and Shaffer, 1997, 2009) were revised. The revised versions of both Tutorials can be found in Appendices B.2 and B.5.

Newly Developed Tutorial Potential

As documented in Section 9.6, a new Tutorial titled *Potential* was developed and evaluated. The Tutorial introduced students to the concept of the electric potential to help them overcome difficulties with their understanding of voltage. As reported in that section, the Tutorial substantially reduced the frequency of the belief that there is no voltage across an open switch. The full Tutorial can be found in Appendix B.8.

11.3 LIMITATIONS OF THIS WORK

This thesis focused on data gathered mostly at one German university, specifically TUHH. In the author's opinion, there is no reason to assume any significant difference between students at TUHH and students at other German universities. The author has also worked at Karlsruhe University of Applied Sciences. Based on his informal classroom observations during several teaching assistant (TA) training sessions, the author would suggest to assume that the results presented in this thesis also apply to students at universities of applied sciences. However, there currently is no data available to prove this assumption.

Most data was gathered in the course EE1ME. This course did not introduce students to the electric potential in its traditional instruction. It is unclear if the effect of the Tutorial is different in courses that also introduce the electric potential in their traditional instruction.

The Tutorial *Potential* was only tested in a lecture hall setting. While the author does not believe that the effect of the Tutorial would be significantly different in a recitation section setting, this difference has not been investigated.

Some of the data presented in this study was gathered at Loughborough University in the United Kingdom (UK). While in some aspects, students at that university were similar to those at TUHH, there were stark differences in other aspects. Based on these inconsistent data, the author would caution to assume that all the results presented in this thesis applied to students in other countries. However, some observations about students at TUHH certainly also apply to students in other countries, as was for example shown in Section 7.4. Nevertheless, care has to be taken with misconceptions that might be influenced by every-day language, like possibly the belief that current is "used up".

11.4 POSSIBLE FUTURE WORK

To the author's knowledge, this thesis is the first dissertation in the field of discipline based electrical engineering education research in Germany. Thus, there is a wide, open field of possible future work.

Specific aspects investigated in this thesis could be investigated further. Most importantly, the research on students' understanding of open and short circuits should be continued. While several misconceptions were identified that could cause students to believe that there is no voltage across open switches and circuits, the frequency of these misconceptions could not be established, due to difficulties in differentiating them verbally. Different research methods than those used in this thesis might lead to an estimation of the frequency of the misconceptions that would enable the development of instruction specifically targeted at the most common ones. Additionally, it was not possible to determine why students' difficulties with identifying short circuits decreased over time. This could either be the result of students becoming accustomed to reading circuit diagrams or be a result of the traditional instruction and Tutorials students participated in. If the former is the reason, it could be valuable to develop a Tutorial to specifically address student misconceptions related to this concept.

Furthermore, there is a need to advance the research presented in this thesis to other fields of electrical engineering. The EERG at TUHH has for example gathered data on students' understanding of the phase relations of capacitances and inductances that has not been discussed in this thesis.

In general, the discussion of electrical engineering concepts in the context of threshold concepts should be continued. In the author's opinion, that framework is a useful tool to identify the concepts instruction should focus on. These concepts and related misconceptions should be the center of Tutorial worksheets and similar instruction.

APPENDIX

A

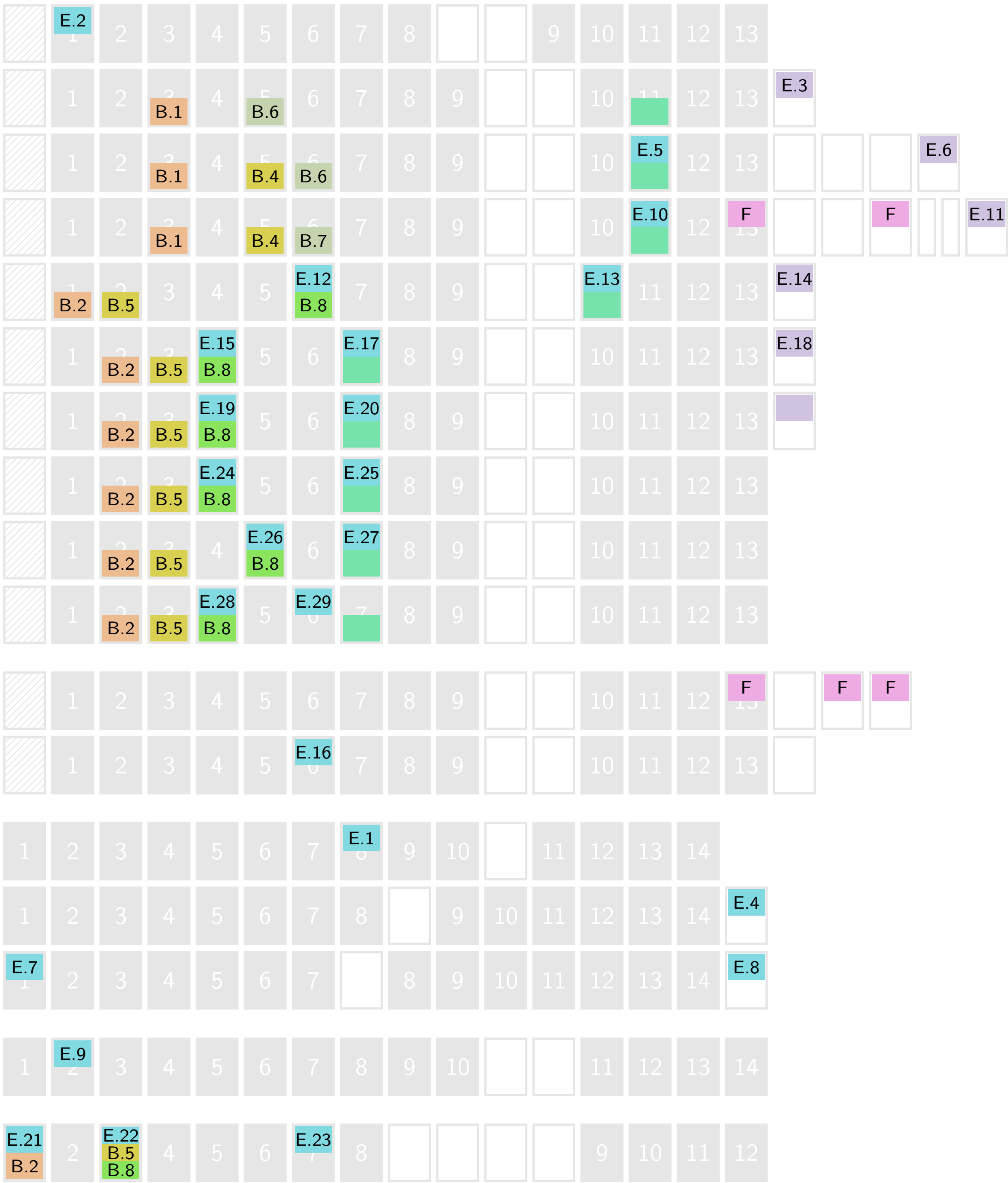
OVERVIEW OF TUTORIALS, TESTS, AND INTERVIEWS IN DIFFERENT COHORTS

This appendix lists the different cohorts, in which the data for this research project was gathered. It details at what points in the semester Tutorials were used and tests and interviews were conducted. The different courses and elements of the semester structure are explained in Chapter 4.

Course	Semester	Start of Semester	Cohort	Instructor
EE1ME	Winter 2008	Oct. 20th, 2008	A	A
	Winter 2011	Oct. 17th, 2011	B	A
	Winter 2012	Oct. 15th, 2012	C	A
	Winter 2013	Oct. 14th, 2013	D	A
	Winter 2014	Oct. 13th, 2014	E	A
	Winter 2015	Oct. 12th, 2015	F	A
	Winter 2016	Oct. 17th, 2016	G	A
	Winter 2017	Oct. 16th, 2017	H	B
	Winter 2018	Oct. 15th, 2018	I	B
	Winter 2019	Oct. 14th, 2019	J	C
EE1EE	Winter 2013	Oct. 14th, 2013	K	D
	Winter 2015	Oct. 12th, 2015	L	D
EE2EE	Summer 2000	Apr. 3rd, 2000	M	E
	Summer 2012	Apr. 2nd, 2012	N	E
	Summer 2013	Apr. 2nd 2013	O	E
EE3EE	Winter 2013	Oct. 14th, 2013	O	F
EE1UK	Semester 2	Feb. 6th, 2017	P	G

Table A.1: Overview of the courses and cohorts data was gathered in, as well as the points in the semester where Tutorials were used and investigations were conducted. Only the cohort O was tested in two different courses. The letters and numbers in the colored boxes indicate the appendix and section the respective test or tutorial is shown in.

Weeks with Lectures, Tutorials, Quizzes, Exams, and Interviews



LEGEND

Week with Lectures

Orientation Week

Week without Lectures

Tutorial *Current and Resistance*

Tutorial *Voltage*

Tutorial *Basic Circuit Analysis*

Tutorial *Potential*

Tutorial *Phase Relations*

Quiz Exam Interview

Letter and number indicate the Appendix the respective quiz, exam, or interview is shown in.

B TUTORIALS

This chapter presents all Tutorials discussed in this thesis in their original German version and an English translation. Relevant excerpts of the English translations are repeated in the main part of the thesis.

The Tutorials shown here are designed to be printed in duplex, i. e. with text on both sides of a sheet of paper. Consequently, a student can usually only see page 1 or pages 2 and 3 or pages 4 and 5 at the same time. Benefiting from this page order, some Tutorials intentionally place summaries at the start of even-numbered pages, so that students can only see them after turning the page. However, to allow for a better comparison of the German original and English translation, the Tutorials are printed here one page at a time, with the German original at left and the English translation at right.

B.1 CURRENT AND RESISTANCE, ORIGINAL VERSION

The Tutorial *Current and Resistance* has a long history. The first published version was called *A model for circuits part 1: Current and resistance* and was part of the *Tutorials in Introductory Physics* (McDermott and Shaffer, 1998). Kautz, Gloss, and Liebenberg created a German translation of the book, called *Tutorien zur Physik* (McDermott and Shaffer, 2009). Kautz (2010) later also created a collection of German Tutorials on Electrical Engineering, called *Tutorien zur Elektrotechnik*. The first Tutorial of that book is called *Strom und Widerstand* (Current and Resistance) and is largely based on the respective Tutorial from the *Tutorien zur Physik*. The translation into German introduced numerous changes in the wording. For the book *Tutorien zur Elektrotechnik*, the Tutorial was altered again, most obviously by introducing boxes that mark given information. Some smaller changes like the addition of task 2.2.c were also made.

The version printed here is labeled as *original version* and was used in the course EE1ME in the winter term 2013. It is practically identical to the Tutorial in the *Tutorien zur Elektrotechnik*. In winter terms 2011 and 2012, the course had used an almost identical version of the Tutorial, which had not used boxes to highlight given information and had had other minor differences.

Appendix B.2 will present a revised version of the Tutorial that was created as part of this thesis.

Im vorliegenden Tutorial entwickeln wir eine Modellvorstellung für den elektrischen Strom, mit der wir das Verhalten einfacher Stromkreise erklären und vorhersagen können.

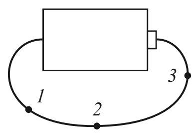
1 Vollständige Stromkreise

1.1 Lassen Sie sich eine Batterie, eine Glühlampe und ein einzelnes Stück Draht geben. Verbinden Sie diese in unterschiedlicher Weise und beobachten Sie jeweils, ob die Lampe leuchtet oder nicht.

Formulieren Sie die Bedingungen, welche die Anordnung der Bauteile erfüllen muss, damit die Glühlampe leuchtet.

1.2 Ein Student hat die beiden Pole einer Batterie für kurze Zeit mit einem Stück Draht verbunden. Er beobachtet, dass sich der Draht an den Punkten 1, 2 und 3 etwa gleich stark erwärmt. Die Batterie wird ebenfalls warm.

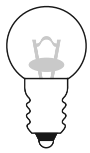
Was lässt sich aufgrund dieser Beobachtung über die Vorgänge an verschiedenen Stellen im Draht und in der Batterie folgern?

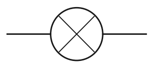


1.3 Bringen Sie eine Glühlampe mit einer Batterie und einem Draht zum Leuchten. Fügen Sie nun Gegenstände aus unterschiedlichen Materialien in die Schaltung ein und beobachten Sie das Verhalten (d. h. die Helligkeit) der Glühlampe. Verwenden Sie Gegenstände wie Papierstreifen, Münzen, Bleistiftminen, Stifte, Radiergummis usw.

Welche Gemeinsamkeit haben die meisten der Gegenstände, bei denen die Glühlampe leuchtet?

1.4 Untersuchen Sie eine Glühlampe sorgfältig. Zwei Drähte reichen vom Glühdraht bis in die Fassung. Sie können vermutlich nicht in die Fassung hineinsehen, sollten jedoch in der Lage sein, eine Vermutung darüber zu formulieren, wo diese Drähte angeschlossen sind. Erläutern Sie Ihre Vermutung mithilfe der Beobachtungen in Teil 1.1 bis 1.3.





Schaltsymbol für Glühlampe

Auf der Grundlage der bisherigen Beobachtungen treffen wir die folgenden Annahmen für unsere Modellvorstellung des elektrischen Stromkreises:

- In einem vollständigen Stromkreis tritt ein „Fluss“ auf, der im Kreis von einem Pol der Batterie entlang der Schaltung zum anderen Pol der Batterie, dann durch die Batterie und schließlich erneut durch die Schaltung verläuft. Diesen Fluss nennen wir den *elektrischen Strom*.
- Bei identischen Glühlampen kann man die Helligkeit der Glühlampen als ein relatives Maß für die Stärke des Stroms durch die Glühlampe verwenden: Je heller eine Glühlampe leuchtet, desto größer ist der Strom, der durch sie fließt.

Ausgehend von diesen Annahmen werden wir eine Modellvorstellung entwickeln, mithilfe derer wir das Verhalten einfacher Stromkreise erklären können. Die Konstruktion eines wissenschaftlichen Modells ist ein schrittweiser Prozess, bei dem wir nur so viele Annahmen machen wie unbedingt notwendig, um die beobachteten Vorgänge zu erklären.

Page 1 of the Tutorial *Current and Resistance*, original version, German original.

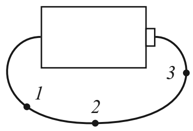
In this tutorial, we construct a model for electric current that we can use to predict and explain the behavior of simple electric circuits.

1 Complete circuits

1.1 Obtain a battery, a light bulb, and a single piece of wire. Connect these in a variety of ways and observe whether the bulb lights up or not.

State the requirements for the arrangement of the three elements that must be met in order for the bulb to light.

1.2 A student has briefly connected a wire across the terminals of a battery. The student finds that the wire seems to be equally warm at points 1, 2, and 3. The battery heats up, too.

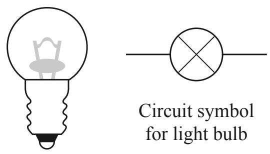


Based on this observation, what might you conclude is happening at the different points in the wire and in the battery?

1.3 Light a bulb using a battery and a single wire. Observe and record the behavior (i. e., brightness) of the bulb when objects made out of various materials are inserted into the circuit. (Try materials such as paper, coins, pencil lead, pens, eraser, etc.)

What is similar about most of the objects that let the bulb light up?

1.4 Carefully examine a bulb. Two wires extend from the filament of the bulb into the base. You probably cannot see into the base, however, you should be able to make a good guess as to where the wires are attached. Explain based on your observations in parts 1.1 through 1.3.



Circuit symbol for light bulb

On the basis of the observations that we have made, we will make the following assumptions for our model for the electric current:

- A "flow" exists in a complete circuit from one terminal of the battery, through the rest of the circuit, back to the other terminal of the battery, through the battery, and back around the circuit. We will call this flow *electric current*.
- For identical bulbs, bulb brightness can be used as an indicator of the amount of current through that bulb: the brighter the bulb, the greater the current through it.

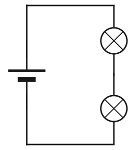
Starting with these assumptions, we will develop a model that we can use to account for the behavior of simple circuits. The construction of a scientific model is a step-by-step process in which we make as few assumptions as possible to explain the phenomena under consideration.

Page 1 of the Tutorial *Current and Resistance*, original version, English translation.

2 Glühlampen in Reihenschaltung

Bauen Sie eine Schaltung mit zwei identischen Glühlampen auf, die hintereinander angeordnet sind (siehe Abbildung). Glühlampen, die so verbunden sind, bezeichnet man als *in Reihe* geschaltet.

2.1 Vergleichen Sie die Helligkeiten der beiden Glühlampen. Beachten Sie dabei nur deutliche Unterschiede in der Helligkeit. Kleinere Unterschiede können auch dadurch auftreten, dass „identische" Glühlampen nicht wirklich identisch sind.



Beantworten Sie die folgenden Fragen auf der Grundlage Ihrer Beobachtung und mithilfe der im Anschluss an Teil 1.4 getroffenen Annahmen.

a. Wird der Strom in der ersten Glühlampe „verbraucht" oder ist der Strom durch die beiden Glühlampen gleich groß?

b. Erwarten Sie eine Änderung der Helligkeiten, wenn Sie die beiden Glühlampen vertauschen? Überprüfen Sie Ihre Antwort.

c. Lässt sich allein aufgrund Ihrer bisherigen Beobachtungen entscheiden, in welcher Richtung der elektrische Strom durch den Stromkreis fließt?

2.2 Vergleichen Sie die Helligkeit der beiden Glühlampen in der Reihenschaltung mit der Helligkeit einer einzelnen Glühlampe im Stromkreis (bei gleicher Batterie).

Beantworten Sie die folgenden Fragen auf der Grundlage Ihrer Beobachtung und mithilfe der im Anschluss an Teil 1.4 getroffenen Annahmen.

a. Ist der Strom durch die Glühlampe in einer Schaltung mit einer einzelnen Lampe *größer*, *kleiner* oder *gleich* dem Strom durch dieselbe Glühlampe, wenn diese mit einer weiteren Lampe in Reihe geschaltet ist? Begründen Sie.

b. Was folgt aus Ihrer Antwort auf Frage 2.2.a hinsichtlich des Stroms durch die Batterie in der Schaltung mit einer Glühlampe im Vergleich zum Strom durch die Batterie in der Reihenschaltung von zwei Lampen? Begründen Sie.

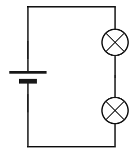
c. Warum ist es nicht richtig, von den beiden in Reihe geschalteten Glühlampen zu sagen, dass sie sich „den Strom durch die Batterie teilen"?

Page 2 of the Tutorial *Current and Resistance*, original version, German original.

2 Bulbs in series

Set up a two-bulb circuit with identical bulbs connected one after the other as shown. Bulbs connected in this way are said to be connected *in series*.

2.1 Compare the brightness of the two bulbs with each other. Pay attention only to large differences in brightness. You may notice minor differences, if two "identical" bulbs are, in fact, not quite identical.



Use your observations and the assumptions we have made in developing our model for electric current after Part 1.4 to answer the following questions:

a. Is current "used up" in the first bulb or is the current the same through both bulbs?

b. Do you think that switching the order of the bulbs might make a difference in brightness? Check your answer.

c. On the basis of your observations *alone*, can you tell the direction in which the current flows through the circuit?

2.2 Compare the brightness of each of the bulbs in the two-bulb series circuit with that of a bulb in a single-bulb circuit (with the same battery).

Use your observations and the assumptions we have made in developing our model for electric current after Part 1.4 to answer the following questions:

a. Is the current through the light bulb of a single-bulb circuit *greater than*, *less than*, or *equal to* the current through the same bulb when it is connected in series with a second bulb? Explain.

b. What does your answer to question 2.2.a imply about the current through the battery in a single-bulb circuit compared to the current through the battery in a two-bulb series circuit? Explain.

c. Why would it be incorrect to say that "the current from the battery is divided" between the two light bulbs in series?

Page 2 of the Tutorial *Current and Resistance*, original version, English translation.

2.3 Wir können uns eine Glühlampe als ein Hindernis oder einen *Widerstand* für den Strom in einem Stromkreis vorstellen.

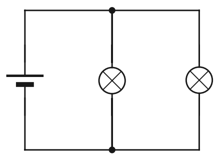
a. Erwarten Sie ausgehend von dieser Vorstellung, dass das Hinzufügen weiterer Glühlampen in Reihe den Widerstand der gesamten Schaltung *vergrößert*, *verkleinert* oder *unverändert lässt*?

b. Formulieren Sie eine Regel, die angibt, ob der Strom durch die Batterie *zunimmt*, *abnimmt* oder *gleich bleibt*, wenn man die Anzahl der in Reihe geschalteten Glühlampen vergrößert oder verkleinert.

3 Glühlampen in Parallelschaltung

Bauen Sie eine Schaltung aus einer Batterie und zwei identischen Glühlampen auf, deren Anschlüsse jeweils miteinander verbunden sind (siehe Abbildung). Glühlampen, die so verbunden sind, bezeichnet man als *parallel* geschaltet.

3.1 Vergleichen Sie die Helligkeiten der beiden Glühlampen in dieser Schaltung. Beachten Sie nur deutliche Unterschiede in der Helligkeit. Kleinere Unterschiede können unter anderem auch dadurch auftreten, dass „identische“ Glühlampen nicht wirklich identisch sind.



a. Was können Sie aus Ihren Beobachtungen über den Strom durch jede der beiden Glühlampen folgern?

b. Beschreiben Sie den elektrischen Strom im gesamten Stromkreis. Gehen Sie dabei von Ihren Beobachtungen aus. Wo teilt sich der von der Batterie kommende Strom und wo wird er wieder zusammengeführt?

3.2 Vergleichen Sie die Helligkeiten der beiden Glühlampen in der Parallelschaltung mit der Helligkeit einer einzelnen Glühlampe im Stromkreis (bei gleicher Batterie). Beachten Sie auch hier nur deutliche Unterschiede in der Helligkeit.

Ist der Strom durch die Batterie in einer Schaltung mit einer einzelnen Glühlampe *größer*, *kleiner* oder *gleich* dem Strom durch die Batterie in einer Schaltung mit zwei parallel geschalteten Glühlampen? Begründen Sie Ihre Antwort mithilfe Ihrer Beobachtungen.

Page 3 of the Tutorial *Current and Resistance*, original version, German original.

2.3 We may think of a bulb as presenting an obstacle, or *resistance*, to the current in the circuit.

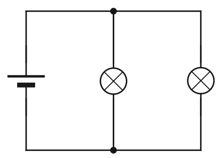
a. Thinking of the bulb in this way, would adding more bulbs in series cause the total obstacle to the flow, or *total resistance*, to *increase*, *decrease*, or *remain the same* as before?

b. Formulate a rule for predicting how the current through the battery would change (*i.e.*, whether it would *increase*, *decrease*, or *remain the same*) if the number of bulbs connected in series was increased or decreased.

3 Bulbs in parallel

Set up a two-bulb circuit with a battery and two identical bulbs so that the terminals of the bulbs are connected with each other. Bulbs connected together in this way are said to be connected *in parallel*.

3.1 Compare the brightness of the two bulbs in this circuit. As before, pay attention only to large differences in brightness. You may notice minor differences, if two “identical” bulbs are, in fact, not quite identical.



a. What can you conclude from your observation about the amount of current through each bulb?

b. Describe the current in the entire circuit. Base your answer on your observations. In particular, where does the current through the battery divide and recombine?

3.2 Compare the brightness of the two bulbs in parallel to the brightness of a single-bulb circuit (with the same battery). As before, pay attention only to large differences in brightness.

Is the current through the battery in a single-bulb circuit *greater than*, *less than*, or *equal to* the current through the battery of a circuit with two light bulbs in parallel? Explain based on your observations.

Page 3 of the Tutorial *Current and Resistance*, original version, English translation.

3.3 Formulieren Sie eine Regel, die angibt, ob der Strom durch die Batterie *zunimmt*, *abnimmt* oder *gleich bleibt*, wenn man die Anzahl der parallel geschalteten Glühlampen vergrößert oder verkleinert. Begründen Sie Ihre Antwort mit Ihren Beobachtungen am Stromkreis mit zwei parallel geschalteten Glühlampen und den Annahmen des Modells für den elektrischen Strom.

Was können Sie über den Widerstand der gesamten Schaltung sagen, wenn die Anzahl der parallel geschalteten Zweige vergrößert oder verkleinert wird?

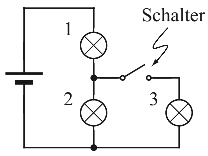
3.4 Deuten Ihre Ergebnisse darauf hin, dass der Strom durch die Batterie von der Anzahl und der Anordnung der Glühlampen in der Schaltung abhängt?

3.5 Schrauben Sie eine der beiden Glühlampen der Parallelschaltung aus ihrer Fassung heraus. Ändert sich dadurch wesentlich der Strom durch den Zweig mit der anderen Glühlampe?

Eine Eigenschaft einer *idealen* Batterie ist, dass unmittelbar an der Batterie angeschlossene, parallele Zweige voneinander unabhängig sind. Ein Modell für das Verhalten *realer* Batterien wird in den Tutorien *Modelleigenschaften* und *Quellen und Arbeitsgeraden* untersucht.

4 Grenzen der bisher entwickelten Modellvorstellung

4.1 Die rechts abgebildete Schaltung enthält drei identische Glühlampen und eine ideale Batterie. Nehmen Sie an, dass der Widerstand der Verbindungsdrähte und des geschlossenen Schalters vernachlässigbar ist. Bearbeiten Sie die folgenden Punkte mithilfe des Modells, das wir für den elektrischen Stromkreis entwickelt haben.



a. Ordnen Sie die drei Glühlampen nach ihrer Helligkeit bei *geschlossenem* Schalter. Begründen Sie.

b. Wie ändert sich die Helligkeit von Glühlampe 1, wenn der Schalter geöffnet wird? Begründen Sie.

4.2 Zeigen Sie, dass die Anwendung der bisher entwickelten Modellvorstellung für den elektrischen Strom nicht ausreicht, um die Änderung der Helligkeit von Glühlampe 2 beim Öffnen des Schalters zu bestimmen.

Page 4 of the Tutorial *Current and Resistance*, original version, German original.

3.3 Formulate a rule for predicting how the current through the battery would change (*i.e.*, whether it would *increase*, *decrease*, or *remain the same*) if the number of bulbs connected in parallel were increased or decreased. Base your answer on your observation of the behavior of the two-bulb parallel circuit and the model for the electric current.

What can you infer about the total resistance of a circuit as the number of parallel branches is increased or decreased?

3.4 Does the amount of current through a battery seem to depend on the number of bulbs in the circuit and how they are connected?

3.5 Unscrew one of the bulbs in the two-bulb parallel circuit. Does this change significantly affect the current through the branch that contains the other bulb?

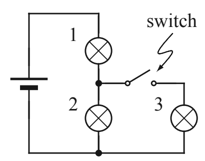
A characteristic of an *ideal* battery is that parallel branches connected directly across it are independent of one another. A model of the behavior of *real* batteries will be covered and examined within the tutorials *Basic Circuit Analysis* and *Sources and Load Lines*.

4 Limitations: The need to extend the model

4.1 The circuit at right contains three identical bulbs and an ideal battery. Assume that the resistance of the closed switch and the wires is negligible. Use the model we have developed to:

a. predict the relative brightness of the bulbs in the circuit with the switch *closed*. Explain.

b. predict how the brightness of bulb 1 changes when the switch is *opened*. Explain.



4.2 Show that the application of the model for the electric current that we have developed thus far is inadequate for determining how the brightness of bulb 2 changes when the switch is opened.

Page 4 of the Tutorial *Current and Resistance*, original version, English translation.

B.2 CURRENT AND RESISTANCE, REVISED VERSION

As part of the research of this thesis, a revised version of the Tutorial *Current and Resistance* (see Appendix B.1) was produced. Section 8.2 describes the research that led to the revision and details the specific changes. The updated version and its English translation are shown on the following pages.

This Tutorial was used in the course EE1ME since winter 2014.

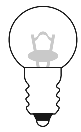
Im vorliegenden Tutorial entwickeln wir eine Modellvorstellung für den elektrischen Strom, mit der wir das Verhalten einfacher Stromkreise erklären und vorhersagen können.

1 Vollständige Stromkreise

1.1 Lassen Sie sich eine Batterie, eine Glühlampe und ein einzelnes Stück Draht geben. Verbinden Sie diese in unterschiedlicher Weise und beobachten Sie jeweils, ob die Lampe leuchtet oder nicht.

Formulieren Sie die Bedingungen, welche die Anordnung der Bauteile erfüllen muss, damit die Glühlampe leuchtet. Spezifizieren Sie welche Teile des Drahtes welche Punkte an der Batterie und an der Glühlampe berühren müssen.

1.2 Untersuchen Sie eine Glühlampe sorgfältig. Zwei Drähte reichen vom Glühdraht bis in die Fassung. Sie können vermutlich nicht in die Fassung hineinsehen, sollten jedoch in der Lage sein, eine Vermutung darüber zu formulieren, wo diese Drähte angeschlossen sind. Erläutern Sie Ihre Vermutung mithilfe der Beobachtungen in Teil 1.1.



Auf der Grundlage der obigen Beobachtungen treffen wir die folgenden Annahmen für unsere Modellvorstellung des elektrischen Stromkreises:

- Das leuchten einer Glühlampe lässt sich darauf zurückführen, dass ein *elektrischer Strom* durch sie fließt.
- Bei identischen Glühlampen kann man die Helligkeit der Glühlampen als ein relatives Maß für die Stärke des Stroms durch die Glühlampe verwenden: Je heller eine Glühlampe leuchtet, desto größer ist der Strom, der durch sie fließt.

Ausgehend von diesen Annahmen werden wir Regeln entwickeln, mithilfe derer wir das Verhalten einfacher Stromkreise erklären können. Die Konstruktion eines solchen *wissenschaftlichen Modells* ist ein schrittweiser Prozess, bei dem wir nur so viele Annahmen machen wie unbedingt notwendig, um die beobachteten Vorgänge zu erklären.

Zur Darstellung von Schaltungen in unserem Modell verwenden wir folgende Symbole:

1.3 Welche Bedingungen muss eine elektrische Schaltung erfüllen, damit überhaupt ein Strom fließen kann?

Basierend auf C. Kautz, *Tutorien zur Elektrotechnik*, © Pearson Studium, 2010

Page 1 of the Tutorial *Current and Resistance*, revised version, German original.

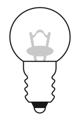
In this tutorial, we construct a model for electric current that we can use to predict and explain the behavior of simple electric circuits.

1 Complete circuits

1.1 Obtain a battery, a light bulb, and a single piece of wire. Connect these in a variety of ways and observe whether the bulb lights up or not.

State the requirements for the arrangement of the three elements that must be met in order for the bulb to light. Which parts of the wire have to be connected to which parts of the bulb and battery?

1.2 Carefully examine a bulb. Two wires extend from the filament of the bulb into the base. You probably cannot see into the base, however, you should be able to make a good guess as to where the wires are attached. Explain based on your observations in part 1.1.



On the basis of the observations that we have made, we will make the following assumptions for our model for the electric current:

- The glowing of a bulb can be explained by an *electric current* flowing through it.
- For identical bulbs, bulb brightness can be used as an indicator of the amount of current through that bulb: the brighter the bulb, the greater the current through it.

Starting with these assumptions, we will develop a model that we can use to account for the behavior of simple circuits. The construction of such a *scientific model* is a step-by-step process in which we make as few assumptions as possible to explain the phenomena under consideration.

The following symbols are used to represent circuit elements in our model:

Bulb: —⊗— Battery: (positive terminal at right) Wire: —— *Connected* Wires:

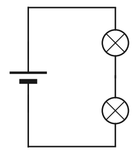
1.3 Which conditions must be met in order for an electric current to flow in a circuit?

Based on C. Kautz, *Tutorien zur Elektrotechnik*, © Pearson Studium, 2010

Page 1 of the Tutorial *Current and Resistance*, revised version, English translation.

2 Glühlampen in Reihenschaltung

Bauen Sie eine Schaltung mit zwei identischen Glühlampen auf, die hintereinander angeordnet sind (siehe Abbildung). Glühlampen, die so verbunden sind, bezeichnet man als *in Reihe* geschaltet.



2.1 Beschreiben Sie den Weg, entlang dessen der elektrische Strom in dieser Schaltung fließt.

2.2 Vergleichen Sie die Helligkeiten der beiden Glühlampen. Beachten Sie dabei nur deutliche Unterschiede in der Helligkeit. Kleinere Unterschiede können auch dadurch auftreten, dass „identische“ Glühlampen nicht wirklich identisch sind.

Beantworten Sie die folgenden Fragen auf der Grundlage Ihrer Beobachtung und mithilfe der im Anschluss an Teil 1.2 getroffenen Annahmen.

a. Wird der Strom in der ersten Glühlampe „verbraucht“ oder ist der Strom durch die beiden Glühlampen gleich groß?

b. Erwarten Sie eine Änderung der Helligkeiten, wenn Sie die beiden Glühlampen vertauschen? Überprüfen Sie Ihre Antwort.

c. Lässt sich allein aufgrund Ihrer bisherigen Beobachtungen entscheiden, in welcher Richtung der elektrische Strom durch den Stromkreis fließt?

2.3 Vergleichen Sie die Helligkeit der beiden Glühlampen in der Reihenschaltung mit der Helligkeit einer einzelnen Glühlampe im Stromkreis (bei gleicher Batterie).

Beantworten Sie die folgenden Fragen auf der Grundlage Ihrer Beobachtung und mithilfe der im Anschluss an Teil 1.2 getroffenen Annahmen.

a. Ist der Strom durch die Glühlampe in einer Schaltung mit einer einzelnen Lampe *größer*, *kleiner* oder *gleich* dem Strom durch dieselbe Glühlampe, wenn diese mit einer weiteren Lampe in Reihe geschaltet ist? Begründen Sie.

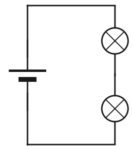
b. Was folgt aus Ihrer Antwort auf Frage 2.3.a hinsichtlich des Stroms durch die Batterie in der Schaltung mit einer Glühlampe im Vergleich zum Strom durch die Batterie in der Reihenschaltung von zwei Lampen? Begründen Sie.

c. Warum ist es nicht richtig, von den beiden in Reihe geschalteten Glühlampen zu sagen, dass sie sich „den Strom durch die Batterie teilen“?

Page 2 of the Tutorial *Current and Resistance*, revised version, German original.

2 Bulbs in series

Set up a two-bulb circuit with identical bulbs connected one after the other as shown. Bulbs connected in this way are said to be connected *in series*.



2.1 Describe the path along which the electric current flows through the circuit.

2.2 Compare the brightness of the two bulbs with each other. Pay attention only to large differences in brightness. You may notice minor differences if two "identical" bulbs are, in fact, not quite identical.

Use your observations and the assumptions we have made in developing our model for electric current after Part 1.2 to answer the following questions:

a. Is current "used up" in the first bulb or is the current the same through both bulbs?

b. Do you think that switching the order of the bulbs might make a difference in brightness? Check your answer.

c. On the basis of your observations *alone*, can you tell the direction in which the current flows through the circuit?

2.3 Compare the brightness of each of the bulbs in the two-bulb series circuit with that of a bulb in a single-bulb circuit (with the same battery).

Use your observations and the assumptions we have made in developing our model for electric current after Part 1.2 to answer the following questions:

a. Is the current through the light bulb of a single-bulb circuit *greater than*, *less than*, or *equal to* the current through the same bulb when it is connected in series with a second bulb? Explain.

b. What does your answer to question 2.3.a imply about the current through the battery in a single-bulb circuit compared to the current through the battery in a two-bulb series circuit? Explain.

c. Why would it be incorrect to say that "the current from the battery is divided" between the two light bulbs in series?

Page 2 of the Tutorial *Current and Resistance*, revised version, English translation.

2.4 Wir können uns eine Glühlampe oder eine Schaltung aus mehreren Glühlampen als ein Hindernis oder einen *Widerstand* für den Strom in einem Stromkreis vorstellen.

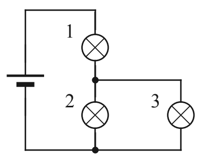
a. Erwarten Sie ausgehend von dieser Vorstellung, dass das Hinzufügen weiterer Glühlampen in Reihe den Widerstand der gesamten Schaltung *vergrößert*, *verkleinert* oder *unverändert lässt*?

b. Formulieren Sie eine Regel, die angibt, ob der Strom durch die Batterie *zunimmt*, *abnimmt* oder *gleich bleibt*, wenn man die Anzahl der in Reihe geschalteten Glühlampen vergrößert oder verkleinert.

3 Stromfluss an Verzweigungen

Bauen Sie eine Schaltung aus einer Batterie und drei identischen Glühlampen auf, wie sie in der Abbildung dargestellt ist.

3.1 Vergleichen Sie die Helligkeiten der drei Glühlampen in dieser Schaltung. Beachten Sie nur deutliche Unterschiede in der Helligkeit. Kleinere Unterschiede können unter anderem auch dadurch auftreten, dass „identische" Glühlampen nicht wirklich identisch sind.



a. Was können Sie aus Ihren Beobachtungen folgern? Vergleichen Sie die Ströme durch Lampe 1, Lampe 2 und Lampe 3.

b. Beschreiben Sie den elektrischen Strom im gesamten Stromkreis. Gehen Sie dabei von Ihren Beobachtungen aus.

Sind Ihre Beobachtungen mit der Vorstellung vereinbar, dass der gesamte Strom nach Passieren von Lampe 1 sowohl durch Lampe 2 als auch durch Lampe 3 fließt?

c. Ist es in diesem Fall richtig zu sagen, dass sich Lampe 2 und Lampe 3 „den Strom teilen"? Begründen Sie.

Inwiefern unterscheidet sich dies von der Situation in 2.3.c?

Page 3 of the Tutorial *Current and Resistance*, revised version, German original.

2.4 We may think of a bulb as presenting an obstacle, or *resistance*, to the current in the circuit.

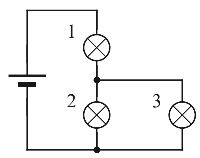
a. Thinking of the bulb in this way, would adding more bulbs in series cause the total obstacle to the flow, or *total resistance*, to *increase*, *decrease*, or *remain the same* as before?

b. Formulate a rule for predicting how the current through the battery would change (*i.e.*, whether it would *increase*, *decrease*, or *remain the same*) if the number of bulbs connected in series was increased or decreased.

3 Current flow at junctions

Set up a three-bulb circuit with a battery and identical bulbs as shown at right.

3.1 Compare the brightness of the three bulbs in this circuit. As before, pay attention only to large differences in brightness. You may notice minor differences, if two "identical" bulbs are, in fact, not quite identical.



a. What can you conclude from your observation? Compare the current through bulb 1, bulb 2, and bulb 3.

b. Describe the current in the entire circuit. Base your answer on your observations.

Do your observations agree with the idea that all of the current that flows through bulb 1 also flows through bulb 2 and bulb 3?

c. Is it correct to say that "the current is divided" between bulb 2 and bulb 3?

How is this situation different to the one in 2.3.c?

Page 3 of the Tutorial *Current and Resistance*, revised version, English translation.

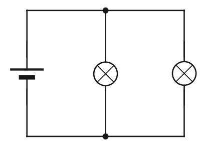
Unsere Beobachtungen legen nahe, dass sich der Strom an Verzweigungen teilt oder vereint und an Knoten kein „neuer Strom entsteht“ oder „Strom verschwindet“. Das Fließen des elektrischen Stromes ähnelt in dieser Hinsicht dem Fließen von Wasser in einem geschlossenen Rohrsystem.

Dieses Verhalten von Strom wird als Knotenpunktregel bezeichnet.

4 Glühlampen in Parallelschaltung

Bauen Sie eine Schaltung aus einer Batterie und zwei identischen Glühlampen auf, deren Anschlüsse jeweils miteinander verbunden sind (siehe Abbildung). Glühlampen, die so verbunden sind, bezeichnet man als *parallel* geschaltet.

4.1 Vergleichen Sie die Helligkeiten der beiden Glühlampen in dieser Schaltung. Was können Sie aus Ihren Beobachtungen über den Strom durch jede der beiden Glühlampen folgern?



4.2 Vergleichen Sie die Helligkeiten der beiden Glühlampen in der Parallelschaltung mit der Helligkeit einer einzelnen Glühlampe im Stromkreis (bei gleicher Batterie). Beachten Sie auch hier nur deutliche Unterschiede in der Helligkeit.

4.3 Gibt es Punkte in dieser Schaltung, an der sich der Strom teilt oder vereint?

4.4 Ist der Strom durch die Batterie in einer Schaltung mit einer einzelnen Glühlampe *größer*, *kleiner* oder *gleich* dem Strom durch die Batterie in einer Schaltung mit zwei parallel geschalteten Glühlampen?
Begründen Sie Ihre Antwort mithilfe Ihrer Ergebnisse aus den Teilen 4.2 und 4.3.

4.5 Formulieren Sie eine Regel, die angibt, ob der Strom durch die Batterie *zunimmt*, *abnimmt* oder *gleich bleibt*, wenn man die Anzahl der parallel geschalteten Glühlampen vergrößert oder verkleinert. Begründen Sie Ihre Antwort mit Ihren Beobachtungen am Stromkreis mit zwei parallel geschalteten Glühlampen und den Annahmen des Modells für den elektrischen Strom.

Was können Sie über den Widerstand der gesamten Schaltung sagen, wenn die Anzahl der parallel geschalteten Zweige vergrößert oder verkleinert wird?

4.6 Deuten Ihre Ergebnisse darauf hin, dass der Strom durch die Batterie von der Anzahl und der Anordnung der Glühlampen in der Schaltung abhängt?

4.7 Schrauben Sie eine der beiden Glühlampen der Parallelschaltung aus ihrer Fassung heraus. Ändert sich dadurch wesentlich der Strom durch den Zweig mit der anderen Glühlampe?

Page 4 of the Tutorial *Current and Resistance*, revised version, German original.

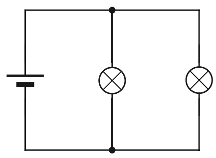
Our observations indicate that the electric current splits and combines at junctions and no "new current is created" or "destroyed". The flow of electric current is in this regard similar to the flow of water in a system of closed pipes.

This behavior of the electric current is referred to as Kirchhoff's Current Law.

4 Bulbs in parallel

Set up a two-bulb circuit with a battery and two identical bulbs so that the terminals of the bulbs are connected with each other. Bulbs connected together in this way are said to be connected *in parallel*.

4.1 Compare the brightness of the two bulbs in this circuit. What can you conclude from your observation about the amount of current through each bulb?



4.2 Compare the brightness of the two bulbs in parallel to the brightness of a single-bulb circuit (with the same battery). As before, pay attention only to large differences in brightness.

4.3 Are there points in this circuit where the current splits or combines?

4.4 Is the current through the battery in a single-bulb circuit *greater than*, *less than*, or *equal to* the current through the battery of a circuit with two light bulbs in parallel? Explain based on your answers in parts 4.2 and 4.3.

4.5 Formulate a rule for predicting how the current through the battery would change (*i.e.*, whether it would *increase*, *decrease*, or *remain the same*) if the number of bulbs connected in parallel were increased or decreased. Base your answer on your observation of the behavior of the two-bulb parallel circuit and the model for the electric current.

What can you infer about the total resistance of a circuit as the number of parallel branches is increased or decreased?

4.6 Does the amount of current through a battery seem to depend on the number of bulbs in the circuit and how they are connected?

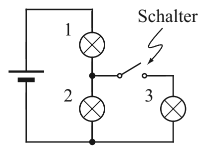
4.7 Unscrew one of the bulbs in the two-bulb parallel circuit. Does this change significantly affect the current through the branch that contains the other bulb?

Page 4 of the Tutorial *Current and Resistance*, revised version, English translation.

Eine Eigenschaft einer *idealen* Batterie ist, dass unmittelbar an der Batterie angeschlossene, parallele Zweige voneinander unabhängig sind. Ein Modell für das Verhalten *realer* Batterien wird in den Tutorien *Modelleigenschaften* und *Quellen und Arbeitsgeraden* untersucht.

5 Grenzen der bisher entwickelten Modellvorstellung

Die rechts abgebildete Schaltung entspricht der aus Abschnitt 3, ergänzt um einen Schalter. Nehmen Sie an, dass der Widerstand des geschlossenen Schalters (wie der von Verbindungsdräthen) vernachlässigbar ist. Bearbeiten Sie die folgenden Aufgaben mithilfe des Modells, das wir für den elektrischen Stromkreis entwickelt haben, d. h. zunächst ohne die Schaltung aufzubauen.



5.1 Leuchtet Lampe 1 nach Ihrer Vermutung bei geschlossenem Schalter *heller*, *gleich hell* oder *weniger hell* als bei offenem Schalter? Begründen Sie mithilfe des Modells.

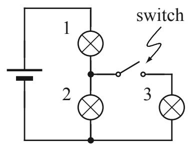
5.2 Zeigen Sie, dass die Anwendung der bisher entwickelten Modellvorstellung für den elektrischen Strom nicht ausreicht, um die Änderung der Helligkeit von Glühlampe 2 beim Öffnen des Schalters zu bestimmen.

Page 5 of the Tutorial *Current and Resistance*, revised version, German original.

A characteristic of an *ideal* battery is that the branches connected directly across it are independent of one another. A model of the behavior of *real* batteries will be covered end examined within the tutorials *Basic Circuit Analysis* and *Sources and Load Lines*.

5 Limitations: The need to extend the model

The circuit at right is identical to the one from Section 3, except for a switch that was added. Assume that the resistance of the closed switch and the wires is negligible. Answer the following questions based on the model for the electric current that was developed so far and do not build the circuit.



5.1 Predict if the brightness of bulb 1 *increases*, *decreases*, or *stays the same*, when the switch is opened. Explain.

5.2 Show that the application of the model for the electric current that we have developed thus far is inadequate for determining how the brightness of bulb 2 changes when the switch is opened.

Page 5 of the Tutorial *Current and Resistance*, revised version, English translation.

B.3 VOLTAGE, PUBLISHED VERSION

Like the Tutorial *Current and Resistance*, the Tutorial *Voltage* has a long history. It was originally named *A model for circuits part 2: Potential difference* and part of the *Tutorials in Introductory Physics* (McDermott and Shaffer, 1998). For the *Tutorien zur Physik* (McDermott and Shaffer, 2009) it was translated into German by Kautz, Gloss, and Liebenberg. With that translation, the name of the German Tutorial was changed to *Ein Modell für Stromkreise - Teil 2: Spannung*, i. e. the name of the Tutorial changed from "Potential Difference" to "Voltage". The German version of the Tutorial was then modified and extended for the book *Tutorien zur Elektrotechnik* (Kautz, 2010). Two sections, one on voltage across open switches and one on the electric potential, were added. Additionally, boxes were used instead of additional line spacing to highlight given information. A box labeling certain rules developed by the students as Kirchhoff's Voltage Law (KVL) was also added. This version of the Tutorial from the *Tutorien zur Elektrotechnik* is labeled here as the *published version*. It has only been published in German, not in English.

B.4 VOLTAGE, ORIGINAL VERSION

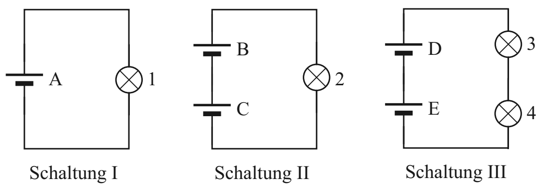
The published version of the Tutorial spanned 7 pages and consequently was too long for most recitation sections. Students would rarely finish the Tutorial and often did not reach the most important tasks. Therefore, the course EE1ME used an abbreviated version in the winter terms 2012 and 2013. This abbreviated version is labeled the *original version*. It did not contain sections 1, 2, 6, and 7 of the published version. The original version and its English translation are shown on the following pages.

Appendix B.5 will present a revised version of the Tutorial that was created as part of this thesis.

Bisher haben wir ein Modell für das Verhalten einfacher Stromkreise entwickelt. Dabei wurde die Helligkeit einer Glühlampe als Anzeige für die Stärke des durch sie fließenden Stroms verwendet. Im vorliegenden Tutorial werden wir dieses Modell um den Begriff der elektrischen Spannung erweitern.

1 Spannung

1.1 Messen Sie den Wert der Spannung an jedem der Elemente in den Schaltungen I bis III mithilfe eines Voltmeters. Notieren Sie die Ergebnisse Ihrer Messungen in der Tabelle.



$U_{\text{Batt A}}$	$U_{\text{Lampe 1}}$	$U_{\text{Batt B}}$	$U_{\text{Batt C}}$	$U_{\text{Lampe 2}}$	$U_{\text{Batt D}}$	$U_{\text{Batt E}}$	$U_{\text{Lampe 3}}$	$U_{\text{Lampe 4}}$

1.2 Ordnen Sie die Glühlampen nach dem Betrag der anliegenden Spannung. (Vernachlässigen Sie dabei kleine Unterschiede.)

Vergleichen Sie die hier gefundene Reihenfolge mit der Reihenfolge nach der Helligkeit.

Die Beobachtung legt nahe, dass wir unser Modell für elektrische Stromkreise um die Vorstellung erweitern können, dass bei identischen Glühlampen die Helligkeit nicht nur ein Maß für den durch sie fließenden *Strom,* sondern auch für die *Spannung* an der Glühlampe ist.

1.3 Welche Anzeige erwarten Sie am Voltmeter, wenn es an dem aus den Batterien D und E bestehenden Netzwerk angeschlossen wird? Begründen Sie Ihre Antwort.

Überprüfen Sie Ihre Vermutung mithilfe eines Voltmeters. Lösen Sie eventuelle Widersprüche auf.

1.4 Welche Anzeige erwarten Sie am Voltmeter, wenn es an dem aus den Glühlampen 3 und 4 bestehenden Netzwerk angeschlossen wird? Begründen Sie Ihre Antwort.

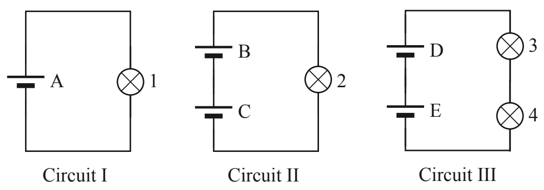
Überprüfen Sie Ihre Vermutungen und lösen Sie eventuelle Widersprüche auf.

Page 1 of the Tutorial *Voltage*, original version, German original.

Previously, we have developed a model to account for the behavior of simple circuits in which bulb brightness can be used as an indicator for the amount of current flowing through that bulb. In this tutorial, we extend this model to include the concept of voltage.

1 Voltage

1.1 Use a voltmeter to measure the voltage across each element in circuits I–III. Record your measurements in the table provided.



$V_{batt\,A}$	$V_{bulb\,1}$	$V_{batt\,B}$	$V_{batt\,C}$	$V_{bulb\,2}$	$V_{Batt\,D}$	$V_{batt\,E}$	$V_{bulb\,3}$	$V_{bulb\,4}$

1.2 Rank the bulbs by the absolute value of the voltage across them. (Ignore any small differences.)

How does the ranking of the bulbs by voltage compare to that by brightness?

The observations above suggest that we can extend our model for electric circuits to include the idea that, for circuits containing identical bulbs, the brightness of a bulb is not only an indicator of the *current* through a bulb, but also an indicator of the *voltage* across it.

1.3 *Predict* what the voltmeter would read if it was connected across the network of batteries D and E. Explain your reasoning.

Use a voltmeter to check your predictions. Resolve any inconsistencies.

1.4 *Predict* what the voltmeter would read if it were connected across the network of bulbs 3 and 4. Explain your reasoning.

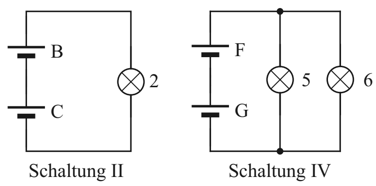
Check your predictions and resolve any inconsistencies.

Page 1 of the Tutorial *Voltage*, original version, English translation.

1.5 Entwickeln Sie anhand Ihrer Beobachtungen eine Regel für die Spannung an einem Netzwerk aus in Reihe geschalteten Elementen. Die Regel soll die Spannung am gesamten Netzwerk mit den Spannungen an den einzelnen Elementen des Netzwerks verknüpfen.

1.6 Betrachten Sie die Schaltungen II und IV in der Abbildung rechts.

a. Welche Reihenfolge erwarten Sie für die Helligkeiten der Glühlampen? Falls zwei Glühlampen die gleiche Helligkeit haben, geben Sie dies ausdrücklich an. Begründen Sie.



Bitten Sie einen Tutor um die Schaltungen und überprüfen Sie Ihre Antwort. Lösen Sie eventuelle Widersprüche auf.

b. Welche Reihenfolge erwarten Sie für die Spannungen an den Glühlampen? Falls an zwei Glühlampen die gleiche Spannung anliegt, geben Sie dies ausdrücklich an. Begründen Sie.

Stimmt Ihre Antwort mit der Reihenfolge der Glühlampen nach der Helligkeit überein?

Überprüfen Sie Ihre Antworten mithilfe eines Voltmeters. Lösen Sie eventuelle Widersprüche auf.

c. Ist der Strom durch die Batterie F *größer, kleiner* oder *gleich* dem Strom durch die Batterie B? Begründen Sie.

1.7 Beantworten Sie die folgenden Fragen anhand Ihrer bisherigen Ergebnisse.

a. Wenn an zwei identischen *Glühlampen* die gleiche Spannung anliegt, fließt dann immer auch der gleiche Strom durch sie hindurch? Begründen Sie.

b. Wenn an zwei identischen *Batterien* die gleiche Spannung anliegt, fließt dann immer auch der gleiche Strom durch sie hindurch? Begründen Sie.

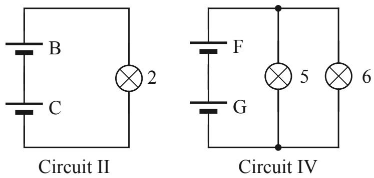
→ Diskutieren Sie Ihre Antworten zu Teil 1.7 mit einem Tutor.

Page 2 of the Tutorial *Voltage*, original version, German original.

1.5 Use your observations to devise a rule that relates the voltage across a network of circuit elements that are connected in series to the voltage across each of the elements in the network.

1.6 Consider circuits II and IV, shown at right.

a. *Predict* the ranking of the bulbs by their brightness. If any of the bulbs will have the same brightness, state so explicitly. Explain.



Ask a tutorial instructor for these circuits so that you can check your ranking. Resolve any inconsistencies.

b. Predict the ranking of the bulbs by the voltage across them. If the voltage across any two bulbs will be the same, state so explicitly. Explain.

Is your ranking of the bulbs by voltage consistent with that by brightness?

Use a voltmeter to check your predictions. Resolve any inconsistencies.

c. Is the current through battery F *greater than*, *less than*, or *equal to* the current through battery B? Explain.

1.7 Answer the following questions on the basis of your work so far:

a. If two identical *bulbs* have the same voltage across them, do they necessarily have the same current through them? Explain.

b. If two *batteries* have the same voltage across them, do they necessarily have the same current through them? Explain.

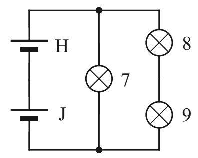
→ Discuss your responses to part 1.7 with a tutorial instructor.

Based on C. Kautz, *Tutorien zur Elektrotechnik*, © Pearson Studium, 2010

Page 2 of the Tutorial *Voltage*, original version, English translation.

2 Schaltungen mit mehreren Maschen

2.1 Betrachten Sie Schaltung V rechts. Welche Anzeige erwarten Sie jeweils, wenn ein Voltmeter an den einzelnen Elementen dieser Schaltung angeschlossen wird? Begründen Sie.

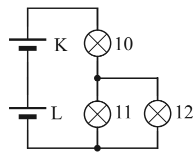


Schaltung V

$U_{\text{Batt H}}$	$U_{\text{Batt J}}$	$U_{\text{Lampe 7}}$	$U_{\text{Lampe 8}}$	$U_{\text{Lampe 9}}$

Bitten Sie einen Tutor um diese Schaltung und überprüfen Sie Ihre Vermutungen. Falls Ihre Messungen nicht mit Ihren Erwartungen übereinstimmen, lösen Sie die Widersprüche auf.

2.2 Betrachten Sie Schaltung VI rechts. Ordnen Sie die Glühlampen nach der anliegenden Spannung. Begründen Sie.



Schaltung VI

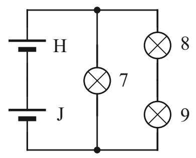
$U_{\text{Batt K}}$	$U_{\text{Batt L}}$	$U_{\text{Lampe 10}}$	$U_{\text{Lampe 11}}$	$U_{\text{Lampe 12}}$

Bitten Sie einen Tutor um diese Schaltung und messen Sie die Spannungen an den einzelnen Elementen. Falls Ihre Messungen nicht mit Ihren Erwartungen übereinstimmen, lösen Sie die Widersprüche auf.

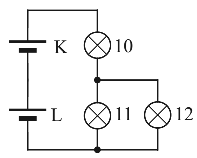
2.3 Die Schaltungen V und VI haben jeweils mehr als einen möglichen Weg für den Strom. Jeder in sich *geschlossene* Weg in einer Schaltung wird als Masche bezeichnet. Eine Masche muss keine Batterie enthalten.

a. Zeichnen Sie in beiden Schaltbildern jeweils alle Maschen ein, die die Batterien enthalten.

b. Berechnen Sie für jede der gezeichneten Maschen die Summe aller Spannungen an den Glühlampen. (Verwenden Sie Ihre obigen Messungen.)



Schaltung V



Schaltung VI

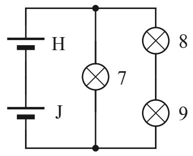
c. Vergleichen Sie die Summe der Spannungen an den Glühlampen in den verschiedenen Maschen mit der Summe der Spannungen der beiden Batterien.

Der hier gefundene Zusammenhang wird als *Maschenregel* bezeichnet.

Page 3 of the Tutorial *Voltage*, original version, German original.

2 Circuits with multiple loops

2.1 Consider circuit V, shown at right. Predict what a voltmeter would read if it was connected across each of the elements in this circuit. Explain.

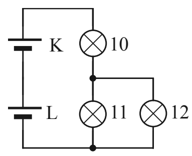


Circuit V

$V_{batt\ H}$	$V_{batt\ J}$	$V_{bulb\ 7}$	$V_{bulb\ 8}$	$V_{bulb\ 9}$

Obtain this circuit from an instructor and check your predictions. If your measurements are not consistent with your prediction, resolve the inconsistencies.

2.2 Consider circuit VI, shown at right. Rank the bulbs by the voltage across them. Explain.



Circuit VI

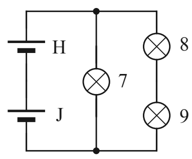
$V_{batt\ K}$	$V_{batt\ L}$	$V_{bulb\ 10}$	$V_{bulb\ 11}$	$V_{bulb\ 12}$

Obtain this circuit from an instructor and measure the voltage across each circuit element. If your measurements are not consistent with your ranking, resolve the inconsistencies.

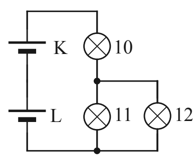
2.3 Circuits V and VI (reproduced at right) each have more than one path for the current. Every *closed* path in a circuit is called a loop (or mesh). It is not necessary for a loop to contain a battery.

a. On each circuit diagram at right, mark all possible current loops that go through the two-battery network.

b. For each current loop that you have drawn, calculate the sum of the voltages across the bulbs in that loop. (Use the measurements you made above.)



Circuit V



Circuit VI

c. How does the sum of the voltages across the bulbs in each loop compare to the sum of the voltages across the two batteries?

The relation observed above is referred to as Kirchhoff's Voltage Law.

Based on C. Kautz, *Tutorien zur Elektrotechnik*, © Pearson Studium, 2010

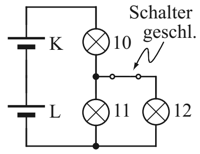
Page 3 of the Tutorial *Voltage*, original version, English translation.

3 Spannung am offenen Schalter

Schaltung VII basiert auf Schaltung VI in Abschnitt 2, enthält jedoch zusätzlich einen Schalter.

3.1 Welche Werte erwarten Sie für die Spannungen an den einzelnen Elementen dieser Schaltung bei geschlossenem Schalter?

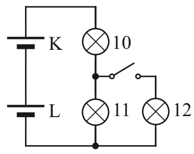
$U_{\text{Batt K}}$	$U_{\text{Batt L}}$	$U_{\text{Lampe 10}}$	$U_{\text{Lampe 11}}$	$U_{\text{Lampe 12}}$



Schaltung VII

3.2 Der Schalter wird nun geöffnet.

a. Welchen Wert erwarten Sie für die Spannung an Lampe 12 bei geöffnetem Schalter?



Schaltung VII

Ist Ihre Antwort mit der von Ihnen erwarteten *Helligkeit* von Lampe 12 vereinbar?

b. Welchen Wert erwarten Sie für die Spannung am offenen Schalter? Begründen Sie.

c. Messen Sie die Spannungen an den einzelnen Elementen der Schaltung (außer dem offenen Schalter).

$U_{\text{Batt K}}$	$U_{\text{Batt L}}$	$U_{\text{Lampe 10}}$	$U_{\text{Lampe 11}}$	$U_{\text{Lampe 12}}$

d. Ist Ihre Vermutung hinsichtlich der Spannung am offenen Schalter mit den gemessenen Spannungen an den anderen Elementen der Schaltung vereinbar?

e. Messen Sie nun die Spannung am offenen Schalter.

Ist Ihr Ergebnis mit der von Ihnen in Teil 2.3.c aufgestellten *Maschenregel* vereinbar? Erläutern Sie ggf., wie Sie diese Regel umformulieren müssen, um sie im vorliegenden Fall anwenden zu können.

Die hier betrachtete Situation wird in Aufgabe 5 in den Übungen weiter vertieft.

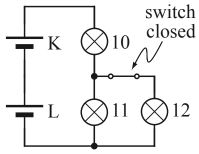
Page 4 of the Tutorial *Voltage*, original version, German original.

3 Voltage across an open switch

Circuit VII is based on circuit VI in section 4. However, a switch was added.

3.1 With the switch being closed, which values do you expect for the voltages across the circuit elements?

$V_{\text{batt K}}$	$V_{\text{batt L}}$	$V_{\text{bulb 10}}$	$V_{\text{bulb 11}}$	$V_{\text{bulb 12}}$

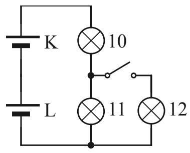


Circuit VII

3.2 Now, the switch is opened.

a. Which value do you expect for the voltage across bulb 12 with the switch being open?

Is you answer consistent with your expected *brightness* of bulb 12?



Circuit VII

b. Which value do you expect for the voltage across the open switch? Explain.

c. Measure the voltage across each circuit element (except the open switch).

$V_{\text{batt K}}$	$V_{\text{batt L}}$	$V_{\text{bulb 10}}$	$V_{\text{bulb 11}}$	$V_{\text{bulb 12}}$

d. Is your assumption regarding the voltage across the open switch consistent with the measured voltage across the other circuit elements?

e. Now, measure the voltage across the open switch.

Is your result consistent with your statement of *Kirhhoff's Voltage Law* in part 2.3.c? Explain, if necessary, how you would have to modify that statement so that it applies in this case.

This situation is further discussed in Task 5 during the exercises.

Page 4 of the Tutorial *Voltage*, original version, English translation.

B.5 VOLTAGE, REVISED VERSION

As part of the research of this thesis, a revised version of the Tutorial *Voltage* (see Appendix B.4) was created. The revised version and its English translation are shown on the following pages. The research that led to these changes is detailed in Section 8.3.1.

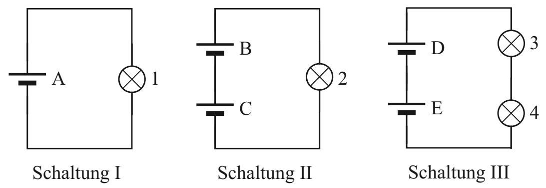
This Tutorial was used in the course EE1ME since winter 2014.

Bisher haben wir ein Modell für das Verhalten einfacher Stromkreise entwickelt. Dabei wurde die Helligkeit einer Glühlampe als Maß für die Stärke des durch sie fließenden Stroms verwendet. Im vorliegenden Tutorial werden wir dieses Modell um den Begriff der elektrischen Spannung erweitern.

1 Spannung

Bitten Sie einen Tutor um die rechts abgebildeten Schaltungen I bis III.

Untersuchen Sie die Helligkeiten der Glühlampen.



1.1 Ordnen Sie die Glühlampen nach der Stärke des durch sie fließenden Stroms. Falls der Strom durch mehrere Glühlampen gleich groß ist, geben Sie dies ausdrücklich an. Erklären Sie, wie Sie dies ohne Ampèremeter feststellen konnten.

1.2 Angenommen, in einem Stromkreis wird eine Batterie in Reihe zu einer vorhandenen Batterie hinzugefügt. Nimmt der Strom durch den Stromkreis dann *zu, ab* oder bleibt er *gleich*? Begründen Sie.

Die obigen Beobachtungen legen nahe, sich die Batterie als einen „Antrieb" des Stroms durch den Stromkreis vorzustellen. Wir werden diese Vorstellung nun genauer untersuchen.

1.3 Messen Sie den Wert der Spannung an jedem der Elemente in den Schaltungen I bis III mithilfe eines Voltmeters. Notieren Sie die Ergebnisse Ihrer Messungen in der Tabelle.

$U_{\text{Batt A}}$	$U_{\text{Lampe 1}}$	$U_{\text{Batt B}}$	$U_{\text{Batt C}}$	$U_{\text{Lampe 2}}$	$U_{\text{Batt D}}$	$U_{\text{Batt E}}$	$U_{\text{Lampe 3}}$	$U_{\text{Lampe 4}}$

1.4 Messen Sie den Wert der Spannung an drei beliebigen Kabeln. Verallgemeinern Sie ihre Beobachtungen.

1.5 Ordnen Sie die Glühlampen nach dem Betrag der anliegenden Spannung. (Vernachlässigen Sie dabei kleine Unterschiede.)

Vergleichen Sie die hier gefundene Reihenfolge mit der Reihenfolge nach dem Strom.

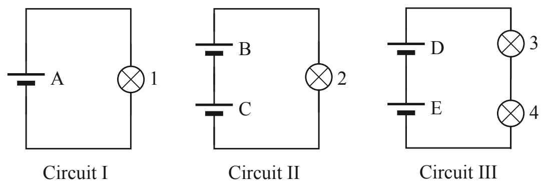
Page 1 of the Tutorial *Voltage*, revised version, German original.

Previously, we have developed a model to account for the behavior of simple circuits in which bulb brightness can be used as a measure for the amount of current flowing through that bulb. In this tutorial, we extend this model to include the concept of voltage.

1 Voltage

Ask a tutorial instructor to hand you the circuits I through III shown at right.

Examine the brightness of the bulbs.



1.1 Rank the bulbs by the amount of current flowing through them. State explicitly, if the current through two bulbs is the same. Explain how you can rank the bulbs without using an ampere meter.

1.2 Assume a battery in a circuit is replaced by two batteries in series. Does the current through the circuit *increase*, *decrease*, or *stay the same*? Explain.

Our observations suggest that batteries can be considered the “motor” of a circuit that causes current to flow. We will examine this idea further.

1.3 Use a voltmeter to measure the voltage across each element in circuits I–III. Record your measurements in the table provided.

$V_{batt\ A}$	$V_{bulb\ 1}$	$V_{batt\ B}$	$V_{batt\ C}$	$V_{bulb\ 2}$	$V_{Batt\ D}$	$V_{batt\ E}$	$V_{bulb\ 3}$	$V_{bulb\ 4}$

1.4 Use a voltmeter to measure the voltage across three wires of your choice. Generalize your findings.

1.5 Rank the bulbs by the absolute value of the voltage across them. Ignore any small differences.

How does the ranking of the bulbs by voltage compare to the ranking by current?

Based on C. Kautz, *Tutorien zur Elektrotechnik*,

Page 1 of the Tutorial *Voltage*, revised version, English translation.

Die Beobachtung legt nahe, dass wir unser Modell für elektrische Stromkreise um die Vorstellung erweitern können, dass bei identischen Glühlampen die Helligkeit nicht nur ein Maß für den durch sie fließenden *Strom,* sondern auch für die *Spannung* an der Glühlampe ist.

1.6 Welche Anzeige erwarten Sie am Voltmeter, wenn es an dem aus den Batterien D und E bestehenden Netzwerk aus Schaltung III (also der Reihenschaltung aus den Batterien D und E) angeschlossen wird? Begründen Sie Ihre Antwort.

Überprüfen Sie Ihre Vermutung mithilfe eines Voltmeters. Lösen Sie eventuelle Widersprüche auf.

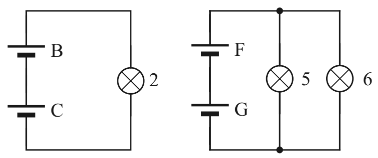
1.7 Welche Anzeige erwarten Sie am Voltmeter, wenn es an dem aus den Glühlampen 3 und 4 bestehenden Netzwerk angeschlossen wird? Begründen Sie Ihre Antwort.

Überprüfen Sie Ihre Vermutungen und lösen Sie eventuelle Widersprüche auf.

1.8 Entwickeln Sie anhand Ihrer Beobachtungen eine Regel für die Spannung an einem Netzwerk aus in Reihe geschalteten Elementen. Die Regel soll die Spannung am gesamten Netzwerk mit den Spannungen an den einzelnen Elementen des Netzwerks verknüpfen.

1.9 Betrachten Sie die Schaltungen II und IV in der Abbildung rechts.

a. Welche Reihenfolge erwarten Sie für die Helligkeiten der Glühlampen? Falls zwei Glühlampen die gleiche Helligkeit haben, geben Sie dies ausdrücklich an. Begründen Sie.



Schaltung II Schaltung IV

Bitten Sie einen Tutor um die Schaltungen und überprüfen Sie Ihre Antwort. Lösen Sie eventuelle Widersprüche auf.

b. Welche Reihenfolge erwarten Sie (ohne Messung) für die Spannungen an den Glühlampen? Falls an zwei Glühlampen die gleiche Spannung anliegt, geben Sie dies ausdrücklich an. Begründen Sie.

Stimmt Ihre Antwort mit der Reihenfolge der Glühlampen nach der Helligkeit überein?

Überprüfen Sie Ihre Antworten mithilfe eines Voltmeters. Lösen Sie eventuelle Widersprüche auf.

c. Ist der Strom durch die Batterie F *größer, kleiner* oder *gleich* dem Strom durch die Batterie B? Begründen Sie.

Basierend auf C. Kautz, *Tutorien zur Elektrotechnik*, © Pearson Studium, 2010

Page 2 of the Tutorial *Voltage*, revised version, German original.

The observations above suggest that we can extend our model for electric circuits to include the idea that, for circuits containing identical bulbs, the brightness of a bulb is not only an indicator of the *current* through a bulb, but also an indicator of the *voltage* across it.

1.6 *Predict* what the voltmeter would read if it was connected across the network of batteries D and E, i. e. the series connection of batteries D and E. Explain your reasoning.

Use a voltmeter to check your predictions. Resolve any inconsistencies.

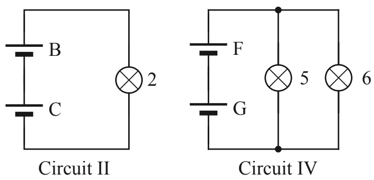
1.7 *Predict* what the voltmeter would read if it was connected across the network of bulbs 3 and 4. Explain your reasoning.

Check your predictions, and resolve any inconsistencies.

1.8 Use your observations to devise a rule that relates the voltage across a network of circuit elements that are connected in series to the voltage across each of the elements in the network.

1.9 Consider circuits II and IV, shown at right.

a. *Predict* the ranking of the bulbs by brightness. If any of the bulbs will have the same brightness, state so explicitly. Explain.



Ask a tutorial instructor for these circuits so that you can check your ranking. Resolve any inconsistencies.

b. Without measuring, predict the ranking of the bulbs by the voltage across them. State explicitly, if the voltage across any two bulbs will be the same. Explain.

Is your ranking of the bulbs by voltage consistent with that by brightness?

Use a voltmeter to check your predictions. Resolve any inconsistencies.

c. Is the current through battery F *greater than*, *less than*, or *equal to* the current through battery B? Explain.

Page 2 of the Tutorial *Voltage*, revised version, English translation.

1.10 Führen Sie Spannungsmessungen an den folgenden 3 Bauteilen durch, wenn diese jeweils nur mit einem Voltmeter verbunden sind. Stimmen Ihre Messergebnisse mit denen aus Schaltung I überein?

Batterie:

Lampe:

Kabel:

1.11 Beantworten Sie die folgenden drei Fragen mithilfe der bisher durchgeführten Messungen. Vernachlässigen Sie dabei kleinere Unterschiede.

a. Ist die Spannung an einer *Batterie* konstant, oder hängt sie von der jeweiligen Schaltung ab, in der diese verbaut ist?

b. Ist die Spannung an einer *Glühlampe* konstant, oder hängt sie von der jeweiligen Schaltung ab, in der diese verbaut ist?

c. Ist die Spannung an einem *Kabel* konstant, oder hängt sie von der jeweiligen Schaltung ab, in der dieses verbaut ist?

1.12 Beantworten Sie die folgenden Fragen anhand Ihrer bisherigen Ergebnisse.

a. Wenn an zwei identischen *Glühlampen* die gleiche Spannung anliegt, fließt dann immer auch der gleiche Strom durch sie hindurch? Begründen Sie.

b. Wenn an zwei identischen *Batterien* die gleiche Spannung gemessen wird, fließt dann immer auch der gleiche Strom durch sie hindurch? Begründen Sie.

1.13 Untersuchen Sie die Aufschriften auf einer Batterie. Finden Sie dort Angaben bezüglich der Spannung oder dem Strom?

Wenn ja, sind diese mit ihren bisherigen Beobachtungen vereinbar?

→ Diskutieren Sie Ihre Antworten zu Teil 1.11 bis 1.13 mit einem Tutor.

Page 3 of the Tutorial *Voltage*, revised version, German original.

1.10 Take the following the circuit elements and connect them individually to a voltmeter. What does the voltmeter read for each element? Do the voltages agree with the ones you measured in circuit I?

Battery:

Bulb:

Wire:

1.11 Answer the following questions, based on the measurements you have done so far. Ignore any small differences.

a. Is the voltage across a *battery* constant or does it depend on the circuit the battery is used in?

b. Is the voltage across a *bulb* constant or does it depend on the circuit the bulb is used in?

c. Is the voltage across a *wire* constant or does it depend on the circuit the wire is used in?

1.12 Answer the following questions on the basis of your work so far:

a. If two identical *bulbs* have the same voltage across them, do they necessarily have the same current through them? Explain.

b. If two *batteries* have the same voltage across them, do they necessarily have the same current through them? Explain.

1.13 Examine the labeling of a battery. Do you find any information about voltage or current?

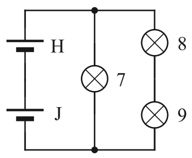
If so, does this agree with your observations so far?

→ Discuss your responses to part 1.11 and 1.13 with a tutorial instructor.

Page 3 of the Tutorial *Voltage*, revised version, English translation.

2 Schaltungen mit mehreren Maschen

2.1 Betrachten Sie Schaltung V rechts. Welche Anzeige erwarten Sie jeweils, wenn ein Voltmeter an den einzelnen Elementen dieser Schaltung angeschlossen wird? Begründen Sie.

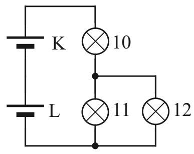


Schaltung V

$U_{\text{Batt H}}$	$U_{\text{Batt J}}$	$U_{\text{Lampe 7}}$	$U_{\text{Lampe 8}}$	$U_{\text{Lampe 9}}$

Bitten Sie einen Tutor um diese Schaltung und überprüfen Sie Ihre Vermutungen. Falls Ihre Messungen nicht mit Ihren Erwartungen übereinstimmen, lösen Sie die Widersprüche auf.

2.2 Betrachten Sie Schaltung VI rechts. Ordnen Sie die Glühlampen nach der anliegenden Spannung. Begründen Sie.



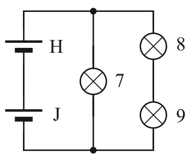
Schaltung VI

Bitten Sie einen Tutor um diese Schaltung und messen Sie die Spannungen an den einzelnen Elementen. Falls Ihre Messungen nicht mit Ihren Erwartungen übereinstimmen, lösen Sie die Widersprüche auf.

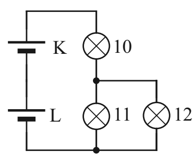
$U_{\text{Batt K}}$	$U_{\text{Batt L}}$	$U_{\text{Lampe 10}}$	$U_{\text{Lampe 11}}$	$U_{\text{Lampe 12}}$

2.3 Die Schaltungen V und VI haben jeweils mehr als einen möglichen Weg für den Strom. Jeder in sich *geschlossene* Weg in einer Schaltung wird als Masche bezeichnet. Eine Masche muss keine Batterie enthalten.

a. Zeichnen Sie in beiden Schaltbildern jeweils alle Maschen ein, die die Batterien enthalten.
b. Berechnen Sie für jede der gezeichneten Maschen die Summe aller Spannungen an den Glühlampen. (Verwenden Sie Ihre obigen Messungen.)



Schaltung V



Schaltung VI

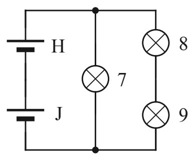
c. Vergleichen Sie die Summe der Spannungen an den Glühlampen in den verschiedenen Maschen mit der Summe der Spannungen der beiden Batterien.

Der hier gefundene Zusammenhang wird als *Maschenregel* bezeichnet.

Page 4 of the Tutorial *Voltage*, revised version, German original.

2 Circuits with multiple loops

2.1 Consider circuit V, shown at right. Predict what a voltmeter would read if it was connected across each of the elements in this circuit. Explain.

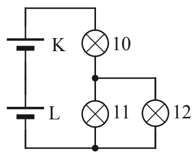


Circuit V

$V_{batt\,H}$	$V_{batt\,J}$	$V_{bulb\,7}$	$V_{bulb\,8}$	$V_{bulb\,9}$

Obtain this circuit from an instructor, and check your predictions. If your measurements are not consistent with your prediction, resolve the inconsistencies.

2.2 Consider circuit VI, shown at right. Rank the bulbs by the voltage across them. Explain.



Circuit VI

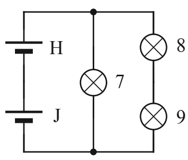
Obtain this circuit from an instructor, and measure the voltage across each circuit element. If your measurements are not consistent with your ranking, resolve any inconsistencies.

V_{battK}	V_{battL}	V_{bulb10}	V_{bulb11}	V_{bulb12}

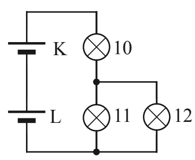
2.3 Circuits V and VI (reproduced at right) each have more than one path for the current. Every *closed* path in a circuit is called a loop (or mesh). It is not necessary for a loop to contain a battery.

a. On each circuit diagram at right, mark all possible current loops that go through the two-battery network.

b. For each current loop that you have drawn, calculate the sum of the voltages across the bulbs in that loop. (Use the measurements you made above.)



Circuit V



Circuit VI

c. How does the sum of the voltages across the bulbs in each loop compare to the voltages across the two batteries?

The relation observed above is referred to as Kirchhoff's Voltage Law.

Page 4 of the Tutorial *Voltage*, revised version, English translation.

B.6 BASIC CIRCUIT ANALYSIS, PUBLISHED VERSION

Basic Circuit Analysis is the English name of the German Tutorial *Modelleigenschaften*, created for the "Tutorien zur Elektrotechnik" (Kautz, 2010, pp. 57-60). It has not been published in English.

This Tutorial had been used in the course EE1ME in winter 2011 and 2012.

B.7 BASIC CIRCUIT ANALYSIS, CUSTOM VERSION

In winter 2013, a custom version of the Tutorial *Basic Circuit Analysis* was used in the course EE1ME. This custom version combined tasks from the published version of the Tutorial *Basic Circuit Analysis* (Appendix B.6) as well as tasks on the electric potential from the published version of the Tutorial *Voltage* (Appendix B.3). Table B.1 describes the origin of the individual tasks.

Table B.1: Composition of the custom version of the Tutorial *Basic Circuit Analysis*. Tasks originating from the published version of the Tutorial *Voltage* are printed in blue font. Tasks originating from the published version of the Tutorial *Basic Circuit Analysis* are printed in black font.

Task	Origin
intro	intro
1.1	6.1*
1.1a	1.1c*
1.1b	1.2a
1.1c	1.2c
2	Box p. 6
2.1a	6.2
2.1b	*new*
2.1c	*new*

Task	Origin
2.1d	*new*
2.1e	*new*
2.2a	6.3
2.2b	6.4
2.3	1.1
2.3a	1.1a*
2.3b	1.1c*
2.3c	1.1b
3.1	1.3, 1st pt.

Task	Origin
3.2	1.3, 2nd pt.**
3.2a	1.3a**
3.2b	1.3b**
3.2c	1.3e*
3.2d	1.3c*
3.2e	1.3d
4	2
4.1	2.2
4.2	results of 2.1

* wording of task slightly altered

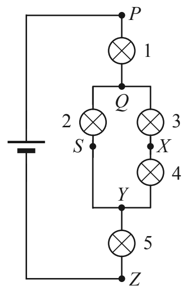
** task heavily altered

Im vorliegenden Tutorial werden einige der bisher eingeführten Begriffe mit dem in der Elektrotechnik üblichen Modell für elektrische Netzwerke formalisiert. Ausserdem soll anhand einiger experimenteller Beobachtungen deutlich werden, welcher Zusammenhang zwischen diesem Modell und realen elektrischen Schaltungen besteht, und wo Unterschiede auftreten.

1 Wiederholung einiger Grundlagen

1.1 *Reihen- und Parallelschaltungen*

Betrachten Sie die nachfolgend dargestellte Schaltung. Die Batterie soll als ideale Spannungsquelle betrachtet werden. Alle leitenden Verbindungen sind widerstandsfrei und alle Glühlampen identisch. Mehrere Punkte (Knoten) in der Schaltung sind markiert.



a. Beschreiben Sie die Schaltung in ihrem Aufbau durch Reihen- und Parallelschaltung einzelner Lampen oder Baugruppen mehrerer Lampen.

b. Formulieren Sie Definitionen der Begriffe „Reihenschaltung“ und „Parallelschaltung“ für Bauelemente (oder Baugruppen) in elektrischen Schaltkreisen. Verwenden Sie dabei *nicht* die Begriffe „Strom“ oder „Spannung“.

- Reihenschaltung

- Parallelschaltung

c. Was lässt sich jeweils über die Ströme durch und Spannungen an zwei Bauelementen aussagen, die in Reihe bzw. parallel geschaltet sind? Begründen Sie Ihre Antwort.

- Reihenschaltung

- Parallelschaltung

1.2 *Strom, Spannung und Helligkeit von Lampen in einfachen Schaltungen*

a. Ordnen Sie mithilfe der Modellvorstellung für den elektrischen Strom die Glühlampen 1 bis 5 nach ihrer Helligkeit.

b. Vergleichen Sie die Spannung an Glühlampe 5 mit der Spannung an Glühlampe 1 mithilfe des Zusammenhangs zwischen Helligkeit und Spannung.

c. Ist die Spannung zwischen Punkt S und der negativen Anschlussklemme der Batterie *grösser, kleiner* oder *gleich* der Spannung zwischen Punkt X und der negativen Anschlussklemme der Batterie?

Welche der beiden Spannungen, die Sie gerade verglichen haben, ist mit der Spannung an einer einzelnen Lampe identisch? Welche nicht?

Basierend auf C. Kautz, *Tutorien zur Elektrotechnik*, ©Pearson Studium, 2010

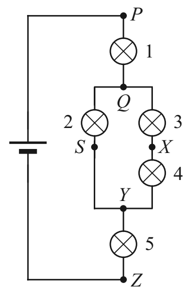
Page 1 of the Tutorial “Basic Circuit Analysis”, custom version, German original.

In the current Tutorial we will formalize some of the previously introduced concepts for electric networks according to the model commonly used in electrical engineering. In addition, we will investigate the connection between this model and real circuits and the limitations of the model through experimental observation.

1 Review of basic concepts

1.1 *Series and parallel connections*

Consider the circuit below. The battery can be treated as an ideal voltage source. All conductive connections are resistance-free and all bulbs are identical. Several points (nodes) in the circuit are marked.



a. Describe the structure of the circuit by identifying series and parallel connections of individual lamps and groups of several lamps.

b. Give definitions of the terms “series” and “parallel” as they apply to electrical connections of circuit elements (or groups of circuit elements). In your definitions, do not refer to current or voltage.

- Series connection:
- Parallel connection:

c. What can be stated about the currents through and voltages across two components connected in series or in parallel? Explain your reasoning.

- Series connection:
- Parallel connection:

1.2 *Current, voltage, and brightness of bulbs in simple circuits*

a. Use the model for electric current in order to rank the light bulbs 1 through 5 according to their brightness.

b. Compare the voltage across bulb 5 with the voltage across bulb 1 considering the correlation between brightness and voltage.

c. Is the voltage between node S and the negative terminal of the battery *greater than*, *less than*, or *equal to* the voltage between node X and the negative terminal of the battery?

Which of the two voltages you have just compared is identical to the voltage on a single bulb? Which is not?

Based on C. Kautz, *Tutorien zur Elektrotechnik*, ©Pearson Studium, 2010

Page 1 of the Tutorial “Basic Circuit Analysis”, custom version, English translation.

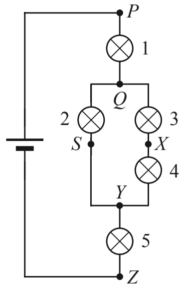
2 Betrachtung von Schaltungen mithilfe des elektrischen Potentials

Um Spannungen zwischen zwei entfernten Punkten in einem Schaltkreis besser bestimmen zu können, führen wir den Begriff des *elektrischen Potentials* ein. Nach der Definition ist die Potential*differenz* zwischen zwei beliebigen Punkten in einem Schaltkreis gleich der Spannung zwischen den beiden Punkten (z. B. $U_{PQ} = \Phi_P - \Phi_Q$).

Das Potential Φ an *jedem beliebigen* Punkt wird dann dadurch festgelegt, dass einem bestimmten Punkt in der Schaltung ein beliebiger Wert zugeordnet wird. Häufig wählt man dafür die negative Klemme der Batterie und ordnet diesem Punkt das Potential $\Phi = 0\,\mathrm{V}$ zu. In diesem Fall besitzt die positive Klemme der Batterie dann das Potential $\Phi = U_{\mathrm{Batt}}$.

2.1 *Potentialstufen im Schaltbild*

Die Schaltung aus Abschnitt 1 ist nebenstehend noch einmal abgebildet.



a. Ordnen Sie die Punkte *P, Q, S, X, Y* und *Z* nach ihrem elektrischen Potential. Begründen Sie.

b. Haben Sie Punkte identifiziert, die gleiches Potential haben? Wenn ja, wie konnten Sie dies feststellen? Wenn nein, warum treten keine Punkte gleichen Potentials auf?

c. Zur Verdeutlichung der verschiedenen Werte des Potentials im Schaltbild soll nun eine farbliche Kodierung verwendet werden. Markieren Sie jeweils *alle* Punkte gleichen Potentials (also jeweils einen gesamten Bereich der Schaltung) mit derselben Farbe (z. B. rot für das höchste auftretende Potential, blau für das niedrigste, usw.).

d. Beschreiben Sie, wie Sie Bereiche gleichen Potentials gefunden haben.

e. Wie lässt sich die farbliche Kodierung der Potentialstufen nutzen, um Bauelemente oder Baugruppen zu identifizieren, die parallel geschaltet sind?

2.2 *Potential und Spannung*

a. Ist es möglich, dass an zwei Elementen in einer Schaltung die gleiche Spannung anliegt, aber alle ihre Klemmen auf unterschiedlichen Potentialen liegen? Wenn ja, geben Sie nach Möglichkeit ein Beispiel aus dem obigen Schaltkreis an. Wenn nein, begründen Sie, warum nicht.

b. Ist es möglich, dass für zwei Elemente in einer Schaltung die Klemme mit dem jeweils höheren Potential auf gleichem Potential liegt, aber an den beiden Elementen unterschiedliche Spannungen anliegen? Wenn ja, geben Sie nach Möglichkeit ein Beispiel aus dem obigen Schaltkreis an. Wenn nein, begründen Sie, warum nicht.

Page 2 of the Tutorial “Basic Circuit Analysis”, custom version, German original.

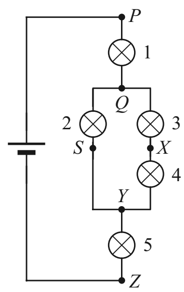
2 Investigation of circuits using the electrical potential

In order to determine the voltage between two distant points in a circuit more easily, we introduce the term *electric potential*. The potential *difference* between two arbitrary points within a circuit is equal to the voltage between those two points. (e. g. $V_{PQ} = \Phi_P - \Phi_Q$).

The potential Φ at *any arbitrary* point is then defined by assigning an arbitrary value to a certain point within the circuit. Often, the negative terminal of a battery is assigned a potential of $\Phi = 0\,\text{V}$. Then, the positive terminal of that battery has the potential $\Phi = V_{\text{Batt}}$.

2.1 *Potentials in a circuit*

The circuit from Part 1 is repeated at right.



a. Order points P, Q, S, X, Y, and Z by their electric potential. Explain.

b. Did you find points that have the same potential? If so, how did you finde these? If not, why are there none?

c. To illustrate the different values of the potential in the circuit diagram, color coding can be used. Mark *all* points of equal potential (i. e. an entire area of the circuit) with the same color (e. g. red for the highest potential, blue for the lowest, etc.).

d. Describe, how you identified points of equal potential.

e. How can you use the color coding to identify circuit elements or groups of circuit elements that are connected in parallel?

2.2 *Potential and Voltage*

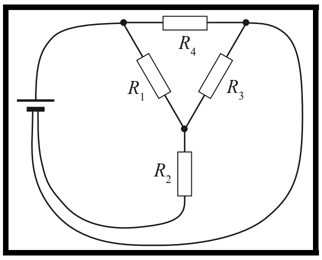
a. Is it possible that the potential difference across two circuit elements is equal while all terminals have different potentials? If so, try to give an example based on the circuit above. If not, explain why not.

b. Is it possible for two circuit elements to have the same potential at the terminal with higher potential, but different voltages across the elements? If so, try to give an example based on the circuit above. If not, explain why not.

Page 2 of the Tutorial “Basic Circuit Analysis”, custom version, English translation.

2.3 ***Anwendungsbeispiel***

Die nebenstehende Abbildung gibt die Drahtverbindungen zwischen den Bauteilen einer Schaltung aus einer Batterie und vier Widerständen wirklichkeitsgetreu wieder.



a. Markieren Sie jeweils alle Bereiche gleichen Potentials mit derselben Farbe.

b. Beschreiben Sie die Schaltung in ihrem Aufbau durch Reihen- und Parallelschaltung der verschiedenen Widerstände oder Baugruppen.

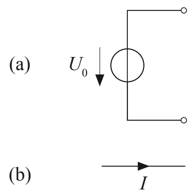
c. Zeichnen Sie nun im nebenstehenden Zeichenfeld ein Schaltbild der gleichen Schaltung in der üblichen rechtwinkligen Form.

3 Die Beschreibung elektrischer Netzwerke

3.1 ***Zählpfeile und Aufstellen von Netzwerkgleichungen***

Das Symbol in Abbildung (a) wird in der Elektrotechnik häufig zur Bezeichnung einer Spannungsquelle verwendet. Dabei gibt der Pfeil die Richtung vom höheren zum niedrigeren Potential an, wenn U_0 einen positiven Zahlenwert hat.

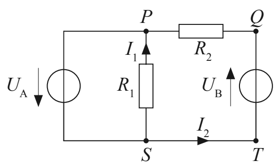
Der Pfeil in Abbildung (b) stellt den Strom durch einen Leiter oder ein Schaltungselement dar. Ein positiver Wert für I entspricht hier einer Bewegung positiver Ladung in Pfeilrichtung.



Beide Arten von Pfeilen werden als *Zählpfeile* bezeichnet. Zählpfeile werden später im Zusammenhang mit der Leistung in elektrischen Systemen erneut betrachtet.

3.2 ***Aufstellen von Netzwerkgleichungen***

In der rechts dargestellten Schaltung sind die beiden Spannungsquellen durch Zählpfeile gekennzeichnet. Ausserdem sind an zwei Stellen Stromzählpfeile eingetragen. U_A und U_B können als bekannt (und positiv) angenommen werden. Die im Schaltbild dargestellten Zusammenhänge sollen nun algebraisch (d.h. in Form von Gleichungen) wiedergegeben werden.



a. Die Punkte P und S sind ausser durch den Widerstand R_1 auch durch die Spannungsquelle U_A miteinander verbunden. Welcher Zusammenhang zwischen den Potentialen Φ_P und Φ_S ist dadurch festgelegt?

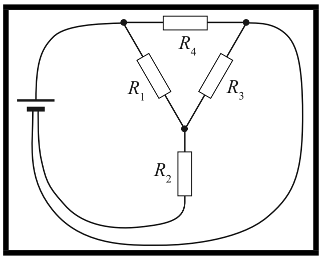
b. Welche zusätzliche Information liefert dann der zwischen P und S eingezeichnete Widerstand R_1?

Basierend auf C. Kautz, *Tutorien zur Elektrotechnik*, ©Pearson Studium, 2010

Page 3 of the Tutorial "Basic Circuit Analysis", custom version, German original.

2.3 *Example*

The following diagram shows a circuit consisting of a battery and four resistors in its actual physical layout.



a. In the circuit, mark all points of equal potential with the same color.

b. Describe the layout of the circuit in terms of series and parallel connections of the resistors or groups of resistors.

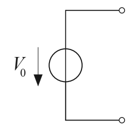
c. In the space provided at right, draw a circuit diagram using the normal rectangular layout.

3 Description of electrical networks

3.1 *Reference directions and network equations*

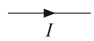
The symbol in picture (a) is commonly used in electrical engineering for representing a voltage source. The arrow indicates the direction from the higher to the lower potential if V_0 has a positive value.

(a)



The arrow in picture (b) indicates the current through a conductor or a circuit element. A positive value for I is related to the movement of positive charge in the direction of the arrow.

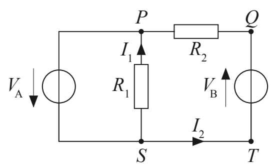
(b)



The convention expressed through these arrows will be used again later in the context of power in electrical systems.

3.2 *Forming network equations*

In the circuit at right, both voltage sources are labeled by arrows indicating the direction of the source voltage. Additionally, two arrows for the direction of currents are given. Assume V_A and V_B to be known (and positive). In the following, the relationships shown in the circuit diagram are to be represented algebraically (i. e. in the form of equations).



a. Points P and S are connected to each other not only by the resistor R_1 but also by the voltage source V_A. What does this imply for the relation between the potentials Φ_P and Φ_S?

b. What additional information is provided by the resistor R_1, which is between P and S?

Page 3 of the Tutorial "Basic Circuit Analysis", custom version, English translation.

c. In den Teilen a und b haben Sie jeweils ein Symbol im Schaltbild durch eine Gleichung wiedergegeben. Stellen Sie nun zwei weitere Gleichungen auf, welche die Symbole für U_B und R_2 in der obigen Schaltung algebraisch wiedergeben.

d. Ordnen Sie Punkt S das Potential 0 V zu und bestimmen Sie die Potentiale an allen anderen markierten Punkten.

Welcher Punkt in der Schaltung hat das höchste, welcher das niedrigste Potential?

e. Bestimmen Sie anhand Ihrer Ergebnisse in Teil c die Vorzeichen der beiden Ströme I_1 und I_2. Begründen Sie.

4 Anwendbarkeit und Grenzen des Modells

4.1 *Ideale und nicht-ideale Spannungsquellen*

Schliessen Sie eine einzelne Glühlampe (Lampe 1) an eine Batterie an. Bauen Sie getrennt davon eine Parallelschaltung von mindestens fünf Glühlampen (ohne Batterie) auf.

a. Verbinden Sie nun das Netzwerk aus den fünf Lampen in Parallelschaltung mit der bereits leuchtenden Lampe 1. Achten Sie darauf, ob sich dabei die Helligkeit von Lampe 1 ändert. Trennen Sie dann wieder die Verbindung zwischen Lampe 1 und den anderen Lampen.

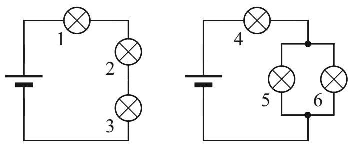
b. Schliessen Sie ein Voltmeter an den Batterieklemmen an. Wiederholen Sie den Versuch und achten Sie nun darauf, ob sich die Klemmenspannung der Batterie ändert.

Wir haben in einem früheren Tutorial beobachtet, dass zwei oder drei Glühlampen, die in Parallelschaltung an eine „gute“ Batterie angeschlossen sind, nahezu die gleiche Helligkeit besitzen wie eine einzelne Lampe an der gleichen Batterie. Wir haben eine Batterie, für welche dies exakt zutrifft, als *ideale Batterie* oder *ideale Spannungsquelle* bezeichnet und festgestellt, dass bei zwei oder drei parallel geschalteten Lampen eine „gute“ Batterie sich nahezu ideal verhält. In diesem Versuch konnten Sie die Grenzen der Anwendbarkeit dieses Modells beobachten. Je mehr Lampen parallel verbunden sind, desto deutlicher werden die Abweichungen vom Verhalten einer idealen Spannungsquelle.

Das Verhalten nicht-idealer Quellen wird im nachfolgenden Tutorial ausführlich untersucht.

4.2 *Ohmsches und nicht-ohmsches Verhalten*

Beobachten Sie die Helligkeit von Lampe 3 im Vergleich mit Lampe 5 oder 6. Notieren Sie Ihre Beobachtung. In einer der Übungsaufgaben zu diesem Tutorial können Sie anhand dieser Beobachtungen nachvollziehen, dass sich Glühlampen *nicht* wie ideale Widerstände verhalten.



Basierend auf C. Kautz, *Tutorien zur Elektrotechnik*, ©Pearson Studium, 2010

Page 4 of the Tutorial “Basic Circuit Analysis”, custom version, German original.

c. In parts a and b, you have represented each symbol in the circuit diagram by one equation. Now set up two further equations, which represent the symbols for V_B and R_2 in the above circuit algebraically.

d. Assign a potential of 0 V to point S and determine the potentials at the other points marked in the circuit.

Which point in the circuit has the highest, which has the lowest potential?

e. On the basis of your results in part c, determine the signs of the currents I_1 and I_2. Explain.

4 Applicability and limits of the model

4.1 *Ideal and non-ideal voltage sources*

Connect a single bulb (bulb 1) to a battery. Also set up a parallel connection of at least 5 bulbs (without a battery).

a. Now connect the network of five bulbs in parallel with the already glowing bulb 1. Observe, if this changes the brightness of bulb 1. Then, disconnect the connection between bulb 1 and the other bulbs.

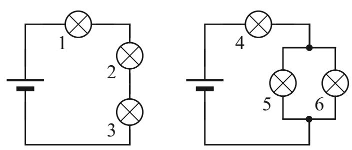
b. Connect a voltmeter across the terminals of the battery. Repeat the experiment and observe whether the voltage of the battery changes.

We had previously observed that two or three bulbs connected across a "good" battery have virtually the same brightness as a single bulb. We called a battery for which this is exactly true an *ideal battery* or *ideal voltage source* and concluded that under the given circumstances a new battery was almost ideal. In this experiment, you were able to observe the limitations of this assumption. The larger the number of bulbs connected in parallel, the greater the deviations from the ideal battery will be.

A more detailed discussion of non-ideal sources will be the topic of the next Tutorial.

4.2 *Ohmic and non-ohmic behavior*

Observe the brightness of bulb 3 compared to bulb 5 or 6. Note your observation. In one of the exercises for this Tutorial you will be able to deduct from these observations that bulbs *do not* behave like ideal resistors.



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Page 4 of the Tutorial "Basic Circuit Analysis", custom version, English translation.

B.8 POTENTIAL

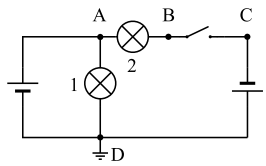
The Tutorial *Potential* was developed as part of Felix Lehmann's bachelor's thesis, which was supervised by the author of this thesis. The author of this thesis also set the design goals of the Tutorial and refined parts of it. It is partially based on Tutorials developed by Kautz (2010) and was used in the course EE1ME since winter 2014.
The development and structure of the Tutorial are described in detail in Section 9.6. The full Tutorial as well as its English translation are shown on the following pages.

POTENTIAL - TUTORIAL 1

Im vorliegenden Tutorial führen wir den Begriff des elektrischen Potentials ein, um Schaltungen besser analysieren zu können. Zusätzlich verwenden wir eine Methode, um Schaltungen übersichtlicher darzustellen.

0 Antwort aus dem Vortest

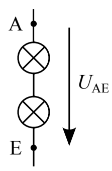
0.1 Sortieren Sie die Spannungen U_{AB}, U_{AC}, U_{AD} und U_{BC} nach ihrem Betrag. Sollten zwei Spannungen gleich groß oder eine Spannung gleich Null sein, geben Sie dies ausdrücklich an. (Versuchen Sie sich an Ihre Antwort aus dem Vortest zu erinnern. Sie werden zu einem späteren Zeitpunkt Gelegenheit haben diese mit ihrem Nachbarn oder ihrer Nachbarin zu diskutieren.)



Schaltung aus dem Vortest

1 Das elektrische Potential in Schaltungen

Ein Potential Φ kann in einer Schaltung jedem beliebigen Punkt auf Leitungen zugeordnet werden. Die Spannung zwischen zwei Punkten ist dann die Differenz der Potentiale. Daraus folgt, dass das Potential ebenso wie die Spannung die Einheit Volt [V] besitzt. Die folgende Gleichung sowie die nebenstehende Grafik zeigen diesen Zusammenhang.



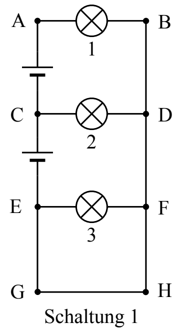
$$U_{AE} = \Phi_A - \Phi_E$$

Dabei ist die Spannung U_{AE} positiv, wenn das Potential Φ_A höher als Φ_E ist. Um die Potentiale in einer Schaltung festzulegen, wird einem beliebigen Punkt (auf einem Kabel) in der Schaltung ein beliebiger Potentialwert zugeordnet. Alle anderen Potentiale sind dann relativ zu diesem Potential festgelegt. An einer Batterie hat die positive Klemme ein um die Batteriespannung höheres Potential als die negative Klemme.

Betrachten Sie die nachfolgend dargestellte Schaltung. Die Batterie soll als eine ideale Spannungsquelle mit 1,5 V angenommen werden. Alle Kabel sind widerstandsfrei und alle Glühlampen identisch. Auf den Leitungen sind die Punkte A bis H markiert.

1.1 Um einen besseren Überblick über die Schaltung zu gewinnen, soll nun eine farbliche Kodierung verwendet werden. Fangen Sie bei einem beliebigen Punkt auf einem Leitungen an und markieren Sie alle Punkte und Leitungen, die nicht durch ein Bauelement von diesem Punkt getrennt sind, mit einer Farbe. Wiederholen Sie dies so lange, bis alle Punkte und Leitungen farblich markiert sind. Wenn möglich, benutzen Sie an Punkt A einen roten Stift und an Punkt E einen blauen Stift.

1.2 Wenn die Leitungen keinen Widerstand haben, was folgt daraus für die Spannung zwischen Punkten auf einer Leitung? Welche Bedeutung haben dann Bereiche mit gleichen Farben?



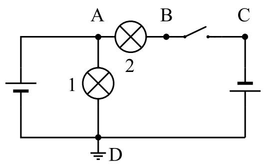
Schaltung 1

Page 1 of the Tutorial *Potential*, German original.

The following Tutorial introduces the concept of the electric potential to improve the analysis of circuits. Additionally, a method is introduced that helps to gain a better overview of a circuit.

0 Pre-Test Answer

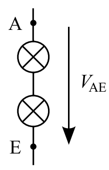
0.1 Rank the voltages V_{AB}, V_{AC}, V_{AD}, and V_{BC} by their absolute value. State explicitly, if two voltages are equally large or a voltage is zero. (Try to remember your answer from the pre-test. At a later point in time, you will be have the chance to discuss your answer with other students.)



Circuit from the pre-test

1 The Electric Potential in Circuits

A potential Φ can be assigned to any point on a wire in a circuit. The voltage between two points is the difference of their potentials. Consequently, the unit of both, voltage and potential, is Volt [V]. The following equation and the figure at right show the relation between voltage and potential:



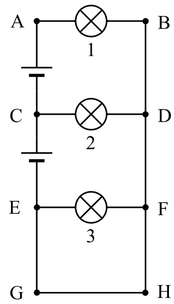
$$V_{\mathrm{AE}} = \Phi_{\mathrm{A}} - \Phi_{\mathrm{E}}$$

The voltage V_{AE} is larger than zero, if the potential Φ_{A} is larger than Φ_{E}. To determine the potentials in a circuit, one arbitrary point (on a wire) is assigned an arbitrary potential. All other potentials are determined relatively to that first potential. The positive terminal of a battery has a potential that is *one battery voltage* higher than that of the negative terminal.

Consider the circuit below. Both batteries can be treated as ideal voltage sources with a source voltage of 1.5 V. The wires have zero resistance and all bulbs are identical. The letters A through H mark points on the wires.

1.1 To obtain a better overview of the circuit, color coding will be used. Start at an arbitrary point on one wire and mark that point with a colored pen. Mark all points and wires that are not separated from this first point by a circuit element with the same color. Repeat this process with different colors until all points and wires are marked. If possible, use red at point A and blue at point E.

1.2 If wires have no resistance, what is the voltage between two points on the same wire? What can you tell about points with the same color?



Circuit I

Page 1 of the Tutorial *Potential*, English translation.

1.3 Ordnen Sie *einer* beliebigen Farbe einen beliebigen Potentialwert zu. Versuchen Sie davon ausgehend alle anderen Potentiale zu ermitteln.

1.4 Überprüfen Sie, ob Ihre Potentiale mit den durch die Batterien vorgegebenen Potentialdifferenzen vereinbar sind. Wenn nicht, ändern Sie die Potentiale entsprechend.

1.5 Bestimmen Sie die Potentialdifferenzen an allen Lampen.

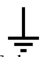
1.6 Ordnen Sie die Lampen nach ihrer Helligkeit. Welcher Zusammenhang zwischen Potentialdifferenz und Helligkeit lässt sich hier anwenden?

1.7 Kann man bei einer Glühlampe (ähnlich wie bei einer Spannungsquelle) immer davon ausgehen, dass die eine Klemme ein höheres Potential hat als die andere Klemme? Begründen Sie.

Diskutieren Sie Ihre Antworten zu Teil 1 mit einem Tutor.

2 Spannung an offenen Schaltern

In der nächsten Schaltung ist nun eine Erdung (wird auch manchmal als Masse bezeichnet) angegeben. Üblicherweise wird der Erdung ein Potential von $0V$ zugeschrieben und alle anderen Potentiale werden auf dieses Potential bezogen.

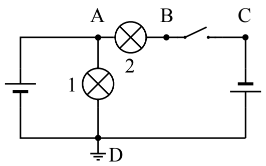


Erdung

Betrachten Sie die nachfolgende Schaltung. Sie enthält neben identischen Glühlampen und idealen Batterien eine Erdung und einen offenen Schalter. Der Schalter bleibt bis Aufgabe 3 geöffnet.

2.1 Markieren Sie alle Punkte und Leitungen entsprechend der Farbkodierung wie in Teil 1.1.

2.2 Weisen Sie allen Farben einen Potentialwert zu.



Schaltung 2

2.3 Sind Ihre Potentialwerte vereinbar mit der Potentialdifferenz an den Batterien? Wenn nicht, ändern Sie Ihre Werte in 2.2 entsprechend.

2.4 Ist Lampe 2 *heller*, *gleich hell*, oder *dunkler* als Lampe 1? Begründen Sie.

Page 2 of the Tutorial *Potential*, German original.

1.3 Assign an arbitrary potential to *one* of the colors. Try to determine all other potentials based on the first one.

1.4 Verify that the potentials you have assigned are not in conflict with the source voltages of the batteries. In case of inconsistencies, adjust the potentials accordingly.

1.5 Determine the potential differences across all three bulbs.

1.6 Rank the bulbs by their brightness. What relationship between potential difference and brightness can be used for this?

1.7 Is it correct to assume that the potentials at the terminals of a bulb (as those of a voltage source) are always different from each other? Explain.

Discuss your answers to Part 1 with a Tutorial instructor.

2 Voltages across open Switches

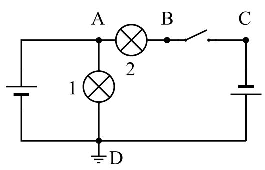
The next circuit contains a grounding (or earthing). By convention, the grounding is assigned a potential of 0 V and all other potentials are measured relative to this ground potential.


Grounding

Consider the following circuit, which contains identical bulbs, ideal batteries with a source voltage of 1.5 V, a grounding, and switch. The switch is in the open position.

2.1 Colorize all points and wires by the color-coding introduced in Section 1.1.

2.2 Assign a potential to each color.



Circuit II

2.3 Check if the values of the potentials fit the potential differences of the batteries. Correct your answer in 2.2 if this is not the case.

2.4 Is bulb 2 *brighter*, *equally bright*, or *dimmer* than bulb 1? Explain.

Page 2 of the Tutorial *Potential*, English translation.

2.5 Was folgt aus der absoluten Helligkeit von Lampe 2 für die Potentialdifferenz an Lampe 2? Ist die Helligkeit mit dem offenen Schalter vereinbar?

2.6 Ordnen Sie nun erneut die Spannungen U_{AB}, U_{AC}, U_{AD} und U_{BC} nach ihrem Betrag. Verwenden Sie zur Bestimmung der Spannungen die Potentiale. Stimmen Ihre Antworten mit denen aus Teil 0.1 überein?

Diskutieren Sie Ihre Ergebnisse mit einem Tutor.

2.7 Wie groß ist die Potentialdifferenz zwischen beiden Enden des (offenen) Schalters?

3 Schaltung nach Schließen des Schalters

In Schaltung 2 wird nun der Schalter geschlossen.

3.1 Zeichnen Sie die Schaltung nach Schließen des Schalters im rechten Kasten und markieren Sie erneut die Punkte A bis D.

Schaltung 3

3.2 Sind die folgenden Spannungen nach Schließen des Schalters betragsmäßig *größer*, *gleich groß* oder *kleiner* als zuvor?

U_{AD}:

U_{AC}:

U_{AB}:

U_{BC}:

3.3 Was haben die beiden Spannungen, die gleich bleiben, gemein?

3.4 Was haben die beiden Spannungen, die sich ändern, gemein?

Diskutieren Sie Ihre Antworten zu 3.3 und 3.4 mit einem Tutor.

3.5 Ist nach Schließen des Schalters Lampe 2 *heller, gleich hell* oder *dunkler* als Lampe 1?

3.6 Sind die Lampen *heller*, *gleich hell* oder *dunkler* als vor Schließen des Schalters? Begründen Sie.

Lampe 1:

Lampe 2:

Page 3 of the Tutorial *Potential*, German original.

2.5 What can you conclude from the brightness of bulb 2 about the potential difference across bulb 2? Does the brightness fit the open switch?

2.6 Rank the voltages V_{AB}, V_{AC}, V_{AD}, und V_{BC} again by their absolute value. Use the potentials to determine the voltages. Does your answer match the answer you gave in Section 0.1?

Discuss your findings with a Tutorial instructor.

2.7 What is the voltage between both ends of the open switch?

3 Circuit with Closed Switch

The switch in circuit II is now closed.

3.1 Draw the circuit with the closed switch in the box at right. Mark points A through D.

3.2 Do the following absolute voltages *increase*, *stay the same*, or *decrease* by closing the switch?

$|V_{\mathrm{AD}}|$:

$|V_{\mathrm{AC}}|$:

$|V_{\mathrm{AB}}|$:

$|V_{\mathrm{BC}}|$:

Circuit III

3.3 What is the same about the two voltages that do not change?

3.4 What is the same about the two voltages that do change?

Discuss your answers to 3.3 and 3.4 with a Tutorial instructor.

3.5 Is bulb 2 *brighter*, *equally bright*, or *dimmer* than bulb 1 after the switch as been closed?

3.6 Are the following bulbs *brighter*, *equally bright*, or *dimmer* than they were before the switch was closed? Explain.

Bulb 1:

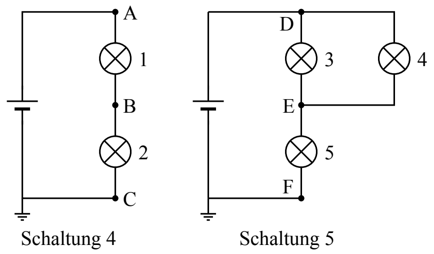
Bulb 2:

Page 3 of the Tutorial *Potential*, English translation.

4 Nicht eindeutig vorbestimmte Potentiale

In den bisherigen Schaltungen ließen sich alle Potentiale eindeutig durch die Zusammenhänge an Bauelementen bestimmen. Wenn dies nicht mehr der Fall ist, müssen wir zusätzliche Methoden anwenden, um eine Schaltung vollständig zu analysieren.
Wir nehmen nun die Glühlampen zunächst als nicht ohmsche Widerstände an, und versuchen unbekannte Potentiale systematisch einzugrenzen.

Die rechts abgebildeten Schaltungen enthalten identische Glühlampen. Die beiden Batterien sind gleich und haben eine konstante Klemmenspannung von 1,5V.



4.1 Können Sie alle Potentiale eindeutig bestimmen? Wenn nicht, schätzen sie die nicht eindeutigen Potentiale ab. Erläutern Sie, wie Sie die Schätzwerte ermittelt haben.

4.2 Ordnen Sie Φ_A bis Φ_C nach ihrer Größe. Ordnen Sie Φ_D bis Φ_F nach ihrer Größe.

4.3 Ordnen Sie die Lampen 1 bis 5 nach ihrer Helligkeit. Wie haben Sie dabei die Lampen aus Schaltung 4 mit den Lampen aus Schaltung 5 verglichen?

4.4 Folgt aus Ihrer Antwort in 4.3, dass Φ_E *größer*, *kleiner* oder *gleich groß* wie Φ_B ist? Begründen Sie.

Diskutieren Sie Ihre Antworten zu den vorherigen Aufgaben mit einem Tutor.

4.5 Bestimmen Sie Φ_B und Φ_E. Nehmen Sie hierfür an, dass die Lampen ohmsche Widerstände sind.

4.6 Ist dieser Spezialfall des ohmschen Widerstands vereinbar mit der Aussage für den allgemeinen Fall in Teil 4.4?

4.7 Ist es für die Potentiale Φ_B und Φ_E relevant, welchen Widerstand die Glühlampen haben? Begründen Sie.

Entgegen der Annahme in Teil 4.5 sind Glühlampen keine ohmschen Widerstände. Dies wird im Tutorial „Modelleigenschaften" näher untersucht.

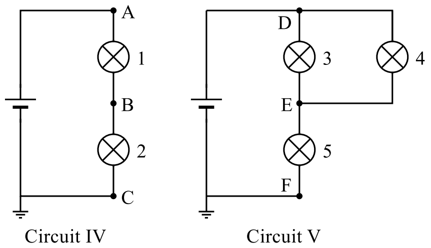
Page 4 of the Tutorial *Potential*, German original.

4 Not explicitly defined potentials

All potentials in the previous circuits could be determined by considering only the circuit elements. With more complex circuits, additional methods have to be used to fully analyze a circuit.
Considering the bulbs to behave as non-ohmic (non-linear) resistors, the possible values of the potentials will be narrowed down systematically.

The circuits at right contain identical bulbs. Both batteries are identical and have a constant source voltage of 1.5 V.

4.1 Is it possible to quantify all potentials? If this is not the case, estimate a value. Explain how you made your estimate.



4.2 Rank Φ_A, Φ_B, and Φ_C by their value. Rank Φ_D, Φ_E, and Φ_F by their value.

4.3 Rank bulbs 1 through 5 by their brightness. How do the brightnesses of the bulbs in circuit IV compare to those in circuit V?

4.4 Consider your answer to 4.3. Is Φ_E *larger*, *equally large*, or *smaller* than Φ_B?

Discuss your answers to Parts 4.3 and 4.4 with a Tutorial instructor.

4.5 Determine Φ_B and Φ_E for the case that the bulbs are ohmic (linear) resistors.

4.6 Are your results for the special case of ohmic resistances the same as for the general case in Part 4.4?

4.7 Does the resistance of the identical bulbs influence the potentials Φ_B and Φ_E? Explain.

Contrary to the assumption in Part 4.5, bulbs are *not* ohmic resistors. Their properties are further examined in the Tutorial *Basic Circuit Analysis*.

Page 4 of the Tutorial *Potential*, English translation.

C

INTENDED OBSERVATIONS AND INFERENCES OF TUTORIALS

Section 8.1 described the development of the Intended Observations and Inferences (IOaI), listings of the critical observations students are supposed to make when working through a Tutorial as well as the inferences they are supposed to make based on their observations. In this appendix, the IOaI of the Tutorials *Current and Resistance* and *Voltage* are printed in full. For each version of these Tutorials, the IOaI are listed separately.

C.1 CURRENT AND RESISTANCE, ORIGINAL VERSION

Listed below are the IOaI of the original version of the Tutorial *Current and Resistance*, which is shown in Appendix B.1 (pp. 309). The IOaI printed in red were considered very important.

These IOaI are used in Section 8.2 (p. 179) to revise the Tutorial Current and Resistance.

1.1 In order for a bulb to light up, a closed circuit has to exist.

1.2 If a wire is connected to a battery to form a closed circuit, the current is the same everywhere in the wire and through the battery.

1.3 A closed loop does not contain any insulators. The closed loop has to be a closed loop of conductors.

1.4 Bulbs have a conducting path between their two terminals, which allows a bulb to be inserted into a closed loop by attaching wires to each terminal of the bulb. Without this conducting path, the bulbs would not light up.

Box A flow exists in a closed circuit. The thing that flows is called current.

The brighter a bulb glows, the more current flows through it.

Objects which allow current to flow, are called conductors, objects that prevent current from flowing are called insulators.

2.1.a Current is not "used up".

2.1.b The two bulbs, I assume to be identical, are identical. Small differences in the brightness of the bulbs are due to the bulbs not being identical.

2.1.c One cannot tell the direction of the flow. The direction does not influence the observations made so far.

2.2.a-b The more bulbs are connected in series, the less current flows through the bulbs and consequently through the entire circuit, including the battery.

2.2.c Not only the same amount of current, but also the same current flows through both bulbs.[1]

2.3-2.3.a The property of a bulb to reduce the current, when inserted into a circuit, is called resistance.

2.3.b The more bulbs are connected in series, the smaller is the current flowing, because of the increased resistance.

3.1 Identical bulbs connected in parallel to a battery are equally bright.

3.1.a Identical bulbs connected in parallel to a battery receive equal current.

3.1.b In a parallel connection, current divides or recombines at junctions.

3.2 Multiple bulbs connected in parallel to a battery are as bright as if they were connected alone. Connecting a second bulb in parallel to a battery does not change the brightness of the first bulb.

Therefore, the current drawn from a battery by a parallel connection of bulbs is greater than that drawn by a single bulb.

3.3 The more bulbs that are connected in parallel to a battery, the greater the current drawn from the battery.

The more bulbs that are connected in parallel to a battery, the smaller the (total) resistance of the circuit.

3.4 The amount of current drawn from a battery in a circuit depends on the number of bulbs in the circuit and how they are connected.

3.5 Adding or removing a bulb in parallel to a battery does not affect the amount of current through other parallel branch(es).

4.1 If two bulbs are connected in parallel and the parallel connection is connected in series with another bulb, the two bulbs in parallel will be dimmer than the single bulb connected in series.

4.2 Not all questions can be answered by the model developed so far.

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1 The IOaI shown here were originally developed with the version of the Tutorial from the *Tutorials in Introductory Physics* (McDermott and Shaffer, 2012), which did not include task 2.2.c. This inference was added later by the author of this thesis.

C.2 CURRENT AND RESISTANCE, REVISED VERSION

Listed below are the IOaI of the revised version of the Tutorial *Current and Resistance*, which is shown in Appendix B.2 (pp. 319). The IOaI printed in red were considered very important.

1.1 In order for a bulb to light up, a closed circuit has to exist.

1.2. If a wire is connected to a battery to form a closed circuit, the current is the same everywhere in the wire and through the battery.

Box A glowing bulb can be explained by current flowing through it.

The brighter a bulb glows, the more current flows through it.

1.3 In order for current to flow, a closed loop has to exist. A battery has to be part of that loop.

2.1.a Current is not "used up".

2.1.b The two bulbs, I assume to be identical, are identical. Small differences in the brightness of the bulbs are due to the bulbs not being identical.

2.1.c One cannot tell the direction of the flow. The direction does not influence the observations made so far.

2.1.d At this point it cannot be decided if current also flows through a battery.

2.2.a-b The more bulbs are connected in series, the less current flows through the bulbs and consequently through the entire circuit, including the battery.

2.3-2.3.a The property of a bulb to reduce the current, when inserted into a circuit, is called resistance.

2.3.b The more bulbs are connected in series, the smaller is the current flowing, because of the increased resistance.

2.3.c Not only the same amount of current, but also the same current flows through both bulbs. [2]

3.1.a If a wire splits, the current through each branch is less than that through the original wire.

3.1.b At nodes, the current splits and/or recombines.

Box This is called Kirchhoff's Current Law.

2 The IOaI shown here were originally developed with the version of the Tutorial from the *Tutorials in Introductory Physics* (McDermott and Shaffer, 2012), which did not include task 2.2.c. This inference was added later by the author of this thesis.

4.1 Identical bulbs connected in parallel to a battery are equally bright.

4.1 Identical bulbs connected in parallel to a battery receive equal current.

4.2 Multiple bulbs connected in parallel to a battery are as bright as if they were connected alone. Connecting a second bulb in parallel to a battery does not change the brightness of the first bulb.

Therefore, the current drawn from a battery by a parallel connection of bulbs is greater than that drawn by a single bulb.

4.3 The more bulbs that are connected in parallel to a battery, the greater the current drawn from the battery.

The more bulbs that are connected in parallel to a battery, the smaller the (total) resistance of the circuit.

4.4 The amount of current drawn from a battery in a circuit depends on the number of bulbs in the circuit and how they are connected.

4.5 Adding or removing a bulb in parallel to a battery does not affect the amount of current through other parallel branch(es).

5.1 If two bulbs are connected in parallel and the parallel connection is connected in series with another bulb, the two bulbs in parallel will be dimmer than the single bulb connected in series.

5.2 Not all questions can be answered by the model developed so far.

C.3 VOLTAGE, PUBLISHED VERSION

Listed below are the IOaI of the published version of the Tutorial *Voltage*, which is described in Appendix B.3 (pp. 331). The IOaI printed in red were considered very important.

1.1 The brightness of a bulb can serve as an indicator of resistance of the entire circuit.

1.2 The current through bulbs in series is always equal to each other.

1.3 If a bulb is connected in series with a battery, the current through both elements is equal.

2.1 Recording of observations, based on "the brighter a bulb glows, the more current flows through it".

2.2 If the ratio of the number of batteries connected in series to the number of bulbs connected in series is equal in two different circuits, the current in both circuits will be equal.

2.3 The more batteries are connected in series, the greater the current.

3.1 Voltage is the property between any two points in a circuit that is measured by a volt-meter, i. e. how far the needle of the volt-meter moves, compared to when it is connected to a standard-battery. If one exchanges the measuring-probes of the volt-meter, i. e. measures the same points but in reverse, the voltage displayed will be the negative of the former value.

3.2 The brighter a bulb, the larger the voltage across it.

3.3 The voltage across a network of batteries connected in series is the sum of the individual voltages of the batteries.

3.4 The voltage across a network of bulbs connected in series is the sum of the individual voltages of the bulbs.

3.5 The voltage across a network of elements connected in series is the sum of the individual voltages of each element.

3.6.a Bulbs connected in parallel to two batteries in series are as bright as a single bulb connected to two batteries in series.

See 3.2.

3.6.b The voltage across bulbs connected in parallel to two batteries in series is equal to the voltage across a single bulb connected to two batteries in series.

3.6.c The current through two batteries connected in series is larger if two bulbs are connected in parallel to them, instead of just one bulb.

3.7.a If the voltage across two bulbs is equal, the current through each is also equal.

3.7.b There is no relation between the voltage across a battery and the current through it.

4.1 If the series connection of two elements is connected in parallel to another element, the sum of the voltages of the two elements in series is equal to the voltage of the parallel element.

4.2 If two bulbs are connected in parallel and this parallel connection is in series with a single bulb, the voltage across the bulbs in parallel is less than that of the single bulb.

4.3 The sum of the voltages across all elements in a closed loop in a circuit is zero.

5.1 The voltage across a closed switch is zero.

5.2 The voltage across an open switch is not necessarily zero.

If the sum of the voltages across all elements of a loop is calculated, the voltages across open switches have to be included.

6.1 The electric potential at any point in the circuit is the voltage between that point and one fixed arbitrary point.

6.2 -

6.3 The difference between the potentials at each end of an element can be equal for two different elements, even if the potentials at each of their ends is different from one another. (The potential differences across two elements can be equal, although their terminals are at different potentials.)

6.4 The difference between the potentials at each end of an element can be different for two different elements, even if the potential at one end of one element is equal to the potential at one end of the other element. (The potential differences across two elements can be different, although the terminals with the higher (or lower) potential are the same.)

7.1 The potential difference across any network connected in parallel to a battery is equal to the potential difference across that battery.

7.2 If two networks are connected in series and this series connection is connected in parallel to a battery, the sum of the potential differences across the networks is equal to the potential difference across the battery.

7.3 If a network consists of bulbs connected in series, the sum of the potential differences across each is equal to the potential difference across the network.

7.4 If a network consists of bulbs connected in parallel, the potential difference across each bulb is equal to the potential difference across the network.

C.4 VOLTAGE, ORIGINAL VERSION

These IOaI are used in Section 8.3 (p. 201) to revise the Tutorial Voltage.

Listed below are the IOaI of the original version of the Tutorial *Voltage*, which is shown in Appendix B.4 (pp. 331). The IOaI printed in red were considered very important.

1.1 Voltage is the property between any two points in a circuit that is measured by a volt-meter, i. e. how far the needle of the volt-meter moves, compared to when it is connected to a standard-battery. If one exchanges the measuring-probes of the volt-meter, i. e. measures the same points but in reverse, the voltage displayed will be the negative of the former value.

1.2 The brighter a bulb, the larger the voltage across it.

1.3 The voltage across a network of batteries connected in series is the sum of the individual voltages of the batteries.

1.4 The voltage across a network of bulbs connected in series is the sum of the individual voltages of the bulbs.

1.5 The voltage across a network of elements connected in series is the sum of the individual voltages of each element.

1.6.a Bulbs connected in parallel to two batteries in series are as bright as a single bulb connected to two batteries in series.

See 1.2.

1.6.b The voltage across bulbs connected in parallel to two batteries in series is equal to the voltage across a single bulb connected to two batteries in series.

1.6.c The current through two batteries connected in series is larger if two bulbs are connected in parallel to them, instead of just one bulb.

1.7.a If the voltage across two bulbs is equal, the current through each is also equal.

1.7.b There is no relation between the voltage across a battery and the current through it.

2.1 If the series connection of two elements is connected in parallel to another element, the sum of the voltages of the two elements in series is equal to the voltage of the parallel element.

2.2 If two bulbs are connected in parallel and this parallel connection is in series with a single bulb, the voltage across the bulbs in parallel is less than that of the single bulb.

2.3 The sum of the voltages across all elements in a closed loop in a circuit is zero.

3.1 The voltage across a closed switch is zero.

3.2 The voltage across an open switch is not necessarily zero.

If the sum of the voltages across all elements of a loop is calculated, the voltages across open switches have to be included.

C.5 VOLTAGE, REVISED VERSION

Listed below are the IOaI of the revised version of the Tutorial *Voltage*, which is shown in Appendix B.5 (pp. 341). The IOaI printed in red were considered very important.

1.1 Recording of observations, based on "the brighter a bulb glows, the more current flows through it".

1.2 The more batteries are connected in series, the greater the current.

1.3 Voltage is the property between any two points in a circuit, that is measured by a volt-meter, i. e. how far the needle of the volt-meter moves, compared to when it is connected to a standard-battery. If one exchanges the measuring-probes of the volt-meter, i. e. measures the same points but in reverse, the voltage displayed will be the negative of the former value.

1.4 The voltage across a wire is always zero.

1.5 The brighter a bulb, the larger the voltage across it.

The larger the current through a bulb, the larger the voltage across it.[3]

1.6 The voltage across a network of batteries connected in series is the sum of the individual voltages of the batteries.

1.7 The voltage across a network of bulbs connected in series is the sum of the individual voltages of the bulbs.

1.8 The voltage across a network of elements connected in series is the sum of the individual voltages of each element.

1.9.a Bulbs connected in parallel to two batteries in series are as bright as a single bulb connected to two batteries in series.

See 1.2.

1.9.b The voltage across bulbs connected in parallel to two batteries in series is equal to the voltage across a single bulb connected to two batteries in series.

1.9.c The current through two batteries connected in series is larger if two bulbs are connected in parallel to them, instead of just one bulb.

3 The IOaI developed in collaboration with Christian Kautz and Ed Dubinsky did not contain an inference for the second part of this task. As that was likely an oversight, this inference was added by the author of this thesis.

1.10-1.11 The voltage across batteries and wires is independent of the circuit they are in, even when the circuit is not closed.

The voltage across a bulb is dependent on the circuit. In an open circuit, the voltage across a bulb is zero.

1.12.a If the voltage across two bulbs is equal, the current through each is also equal.

1.12.b There is no relation between the voltage across a battery and the current through it.

1.13 The (constant) voltage across a battery is printed on that battery. Current is only printed in the context of ampere hours, i. e. charge of the battery.

2.1 If the series connection of two elements is connected in parallel to another element, the sum of the voltages of the two elements in series is equal to the voltage of the parallel element.

2.2 If two bulbs are connected in parallel and this parallel connection is in series with a single bulb, the voltage across the bulbs in parallel is less than that of the single bulb.

2.3 The sum of the voltages across all elements in a closed loop in a circuit is zero.

D

PRELIMINARY GENETIC DECOMPOSITION OF THE TUTORIALS *CURRENT AND RESISTANCE* AND *VOLTAGE*

This appendix presents a genetic decomposition of the content covered in the Tutorials *Current and Resistance* and *Voltage*. It is based on the Intended Observations and Inferences (IOaI) of these two Tutorials (see Appendix C) and must be considered preliminary, as it has not been verified. This document was mostly created by Ed Dubinsky and is discussed in Section 8.5 (p. 206).

D.1 OBJECTS

The elements of a circuit are batteries, bulbs, and switches. Circuit elements can be connected to other circuit elements. The places where these connections are made are called terminals. Each of the elements mentioned above has two terminals. Two or more elements can be connected by attaching the ends of a wire to the terminals of the elements as described below in the section on connections. A wire has two or more ends. That is, wires can branch off and/or combine, therefore connecting more than two terminals.
Batteries, bulbs, switches, and wires are all physical objects or diagrammatic representations of physical objects.

D.2 ACTIONS, PROCESSES, OBJECTS

D.2.1 *Connections*

Connecting circuit elements is an action or process applied to at least one circuit element and at least one wire to obtain a new object, called a network. A network can be treated as an element of a circuit. There are two kinds of connections that have specific names:

SERIES CONNECTION: Two circuit elements are said to be connected in series if a wire with two ends is attached to one terminal of each of the elements. The two terminals not attached to the wire are the terminals of this series connection.

PARALLEL CONNECTION: Two or more circuit elements are said to be connected in parallel if they are connected by two wires as follows. Each wire has one more end than there are circuit elements in the parallel connection. One wire is attached to one terminal of each element, the other wire is attached to the other terminal of each element. The unattached ends of the two wires are the terminals of this parallel connection.

The process of making connections is encapsulated into a cognitive object, called a network.

D.2.2 *Circuits*

A closed loop is a network with the property that from any point in the network, a path that passes once through all circuit elements and wires in the network can be traced back to the same point.
If a network contains at least one battery of which both terminals are part of one closed loop, it is called a circuit.
A circuit is the result of an action or process performed on a set of wires and other elements which are connected as described in the previous paragraph.

D.2.3 *Current*

There are physical objects, which for now remain undefined, that are flowing through circuit elements and wires. The process of these objects flowing we call current, which is thereby encapsulated into an object. Current has several effects, one of which is to cause bulbs in circuits to light up. The amount of current through an element is a quantity assigned to each element. Often, the word "current" is used synonymously for "amount of current", e. g. the question "How does the current through the battery change?" means "How does the amount of current through the battery change?"

D.2.4 *Bulbs*

A bulb is a circuit element that can (depending on the circuit) light up. The brighter a bulb glows, the greater is the amount of current through it and vice versa.

D.2.5 *Resistance*

The property of an element to reduce the amount of current through it is called resistance. Assigning this name encapsulates it into an object. The amount of resistance of one element is greater than that of another if in a single battery circuit the current through the battery is less than if the other element was placed on the first element's place. Bulbs have resistance. We will discuss the resistance of switches and batteries later.

D.2.6 *Conductors, Insulators*

Circuit elements which allow current to flow when inserted into a closed circuit are called conductors, elements that prevent current from flowing when inserted into a closed circuit are called insulators.

D.2.7 *Voltage*

Voltage is an action or process applied to every pair of points in a circuit that results in a movement of the needle in a volt-meter. The amount of voltage is the amount that the needle in the volt-meter moves, measured in terms of a unit which is the amount the needle in the same volt-meter moves when connected to the two terminals of a standard battery. (Whether voltage is an action or a process depends on how a person relates to it. If one actually performs the application it is an action; if the individual thinks about performing it, then it is a process.) Voltage has to be encapsulated from a process to an object in order to apply actions or processes, such as measurement, to it.
Voltage is a property of elements. In case of a battery it is intrinsic in that if you applied a volt-meter – in isolation – you get a reading. In case of a bulb it is extrinsic in that if you applied a voltmeter – in isolation – you get no reading.
If, when measuring a voltage, one interchanges the points between which the voltage is measured, the amount of voltage will be the negative of what it was before.

D.2.8 *Potential*

Potential is a process that assigns a number to each point in a circuit. This is done by selecting a fixed point in a circuit. For each point x in the circuit a volt-meter is applied between x and the fixed point. The reading on the voltmeter is the potential at x.

D.3 PROPERTIES OF A CLOSED CIRCUIT

In this part, actions are applied to objects defined in the first part.

- A circuit is called a closed circuit when a closed path of conducting material exists.
- If a closed circuit consists of only a single conducting path through elements and wires, then the amount of current is the same through any of the elements and wires of the circuit. This comparison of two currents is an action or process on these currents, so the currents must be conceived as objects.

- The brighter a bulb glows, the higher is the amount of current through it. This comparison of brightness and current is an action or process on them, so they must be conceived as objects.
- If two circuit elements are connected in series, the amount of current through both is the same. Again, the comparison of currents is an action on the currents being compared, so they must be conceived as objects.
- The more bulbs that are connected in series, the higher is the resistance in the circuit and so the less the amount of current through each bulb. Consequently the amount of current through the network is reduced.
- Replacing a single bulb with two or more bulbs in parallel – that are identical to the single bulb – increases the amount of current in the circuit. More current is drawn from the battery and the brightness of each bulb is the same as for a single bulb.
- If the current in a circuit divides or recombines at junctions, this does not reduce or increase the amount of current in the circuit.
- Replacing one resistance connected to a battery by a network of resistances of equal magnitude connected to each other in parallel increases the current through the battery.
- The amount of current drawn from a battery depends on the number of resistances in the circuit and how they are connected.
- The amount of current through a battery is larger, if two bulbs are connected in parallel to it instead of just one bulb.
- The brighter a bulb glows, the larger the voltage across it.
- The voltage across a network of circuit elements connected in series is the sum of the individual voltages across the elements.
- If the voltages across two identical bulbs are equal, then the amounts of current through both bulbs are equal.
- There is no relation between the voltage across a battery and the amount of current through it.
- If the series connection of two circuit elements is connected in parallel to a third element, then the sum of the voltages across the first two elements equals the voltage across the third.
- If two identical bulbs are connected in parallel and this network is connected in series with a third identical bulb, then the voltages across each of the first two bulbs are less than that across the third bulb.

- The sum of the voltages across all closed loops in a closed circuit is zero.
- The voltage across a closed switch is zero. The voltage across an open switch may not be zero.
- The potential difference across the two terminals of two circuit elements can be the same, even if the potentials at the respective terminals are different.
- The potential difference across a network connected in parallel to a battery equals the potential difference across the battery.
- If two networks are connected in series and this series connection is connected in parallel to a battery, then the sum of the potential differences across the two networks equals the potential difference across the battery.
- If a network consists of bulbs connected in series, then the sum of the potential differences across each bulb equals the potential difference across the network.
- If a network consists of bulbs connected in parallel, then the potential differences across each bulb equals the potential difference across the network.

E

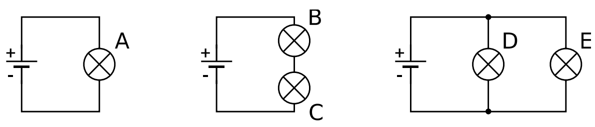
TESTS

This research project used several tests that were given as either ungraded quizzes during lecture time or as part of an exam. These tests are reproduced in full in this appendix. If the original test given to students was in German, the German original as well as an English translation are provided. For tests that used alternate versions, each version is reproduced. Appendix A provides an overview at which point in the semester each test was given.

E.1 QUIZ IN EE1EE, JULY 2000

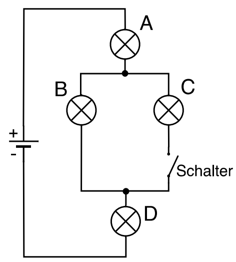
SCHALTUNGEN: STROM UND WIDERSTAND

1. Die folgenden drei Stromkreise bestehen aus identischen Glühlampen und Batterien. Nehmen Sie an, daß die Batterien ideale Spannungsquellen sind (d.h. der Innenwiderstand der Batterien ist Null).



Sortieren Sie die fünf Glühlampen A bis E entsprechend ihrer Helligkeit (unter Verwendung der Symbole >, < oder =). Begründen Sie kurz Ihre Antwort.

2. Die nebenstehende Schaltung enthält eine ideale Batterie, vier identische Glühlampen und einen Schalter.



a. Bei offenem Schalter:

Sortieren Sie die Lampen entsprechend ihrer Helligkeit und begründen Sie Ihre Antwort.

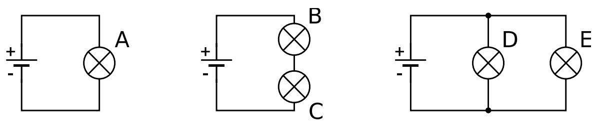
b. Bei geschlossenem Schalter:

Ist die Helligkeit von Glühlampe A für diesen Fall *größer*, *kleiner* oder *gleichbleibend*? Begründen Sie kurz Ihre Antwort.

Quiz in EE1EE, July 2000, German original

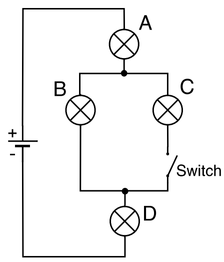
CIRCUITS: CURRENT AND RESISTANCE

1. The following three circuits consist of identical bulbs and batteries. Consider the bulbs to be ideal voltage sources (i.e. their internal resistance is zero).



Rank the five bulbs A to E by their brightness (using the Symbols >, <, or =).
Briefly explain your reasoning.

2. The circuit at right consists of an ideal battery, four identical bulbs and a switch.



   a. When the switch is open:

      Rank the bulbs by their brightness and explain your reasoning.

   b. When the switch is closed:

      Does bulb A glow *brighter*, *dimmer*, or *equally bright* than when the switch is open? Briefly explain your reasoning.

Quiz in EE1EE, July 2000, English translation

E.2 QUIZ IN EE1ME, OCTOBER 30TH, 2008

Mathe-matik	bis Klassenstufe: ………..	Leistungskurs (ja/nein) ………..	Studiengang: MB,SB,VT,BVT,EUT
Physik	bis Klassenstufe: ………..	Leistungskurs (ja/nein) ………..	

Frage 1:

Ordnen Sie die fünf Glühlampen A bis E entsprechend ihrer Helligkeit (unter Verwendung der Symbole >, < und/oder =). Begründen Sie kurz Ihre Antwort.

Frage 2:

	nimmt ab	nimmt zu	unver-ändert
die Helligkeit von Lampen A und B			
die Helligkeit von Lampe C			
der der Batterie entnommene Strom			
die Spannungen an Lampe A und an Lampe B			
die in der gesamten Schaltung umgesetzte Leistung			

Quiz in EE1ME, October 30th, 2008, German original

Math	until grade: ……….	advanced course (yes/no) ………..	Study program: ME,NA,PE,BPE,EEE
Physics	until grade: ……….	advanced course (yes/no) ………..	

Task 1:

Rank the five bulbs A to E by their brightness (use the symbols >, <, and/or =).
Briefly explain your reasoning.

Task 2:

	decreases	increases	stays the same
the brightness of bulbs A and B			
the brightness of bulb C			
the current from the battery			
the voltages across bulbs A and B			
the total power converted in the circuit			

Quiz in EE1ME, October 30th, 2008, English translation

E.3 EXAM IN EE1ME, FEBRUARY 7TH, 2012

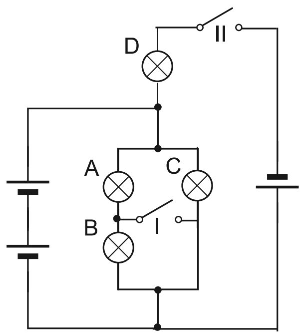
Vorname: **Nachname:**

Matr.-Nr.:

Aufgabe 1 (6 Punkte)

Alle Batterien in der nebenstehenden Schaltung sind identisch und können als ideale Spannungsquellen aufgefasst werden. Der lange dünne Strich bezeichnet jeweils den Pluspol der Batterie. Die vier Lampen sind ebenfalls identisch und vertragen alle auftretenden Spannungen.

Geben Sie zu Ihrer Antwort auf folgende Fragen jeweils eine kurze Begründung an.



		Antwort hier eintragen
a)	(2 Punkte) Die Schalter I und II sind geöffnet: Ordnen Sie die Lampen A, B, C und D nach ihrer Helligkeit. Falls zwei Lampen gleich hell sind oder eine Lampe gar nicht leuchtet, geben Sie dies ausdrücklich an.	
Begründung:		
b)	(2 Punkte) Schalter I wird geschlossen. Schalter II bleibt offen: Leuchtet Lampe A *heller, gleich hell* oder *weniger hell* als zuvor? Leuchtet Lampe C *heller, gleich hell* oder *weniger hell* als zuvor?	
Begründung:		
c)	(2 Punkte) Schalter I wird wieder geöffnet. Schalter II wird geschlossen: Leuchtet Lampe C *heller, gleich hell* oder *weniger hell* als in Aufgabenteil a)? Welche der vier Lampen leuchtet am hellsten?	
Begründung:		

Exam in EE1ME, February 7th, 2012, Task 1, German original

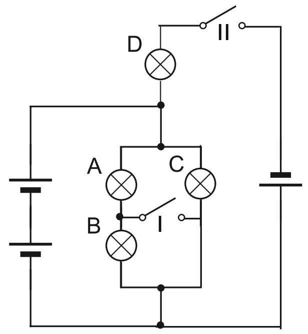
First name: **Last Name:**

Matriculation number:

Task 1 (6 points)

The circuit at right contains identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery. The four bulbs are identical. All occurring voltages are within operating range of the bulbs.

Give a short reasoning for every answer to the following questions.



		Answer
a)	(2 points) The switches I and II are open: Rank the bulbs A, B, C and D by their brightness. State explicitly, if two bulbs have the same brightness or one bulb does not glow at all.	
Reasoning:		
b)	(2 points) Switch I is closed now. Switch II stays open: Does bulb A glow *brighter*, *equally bright* or less bright than before? Does bulb C glow *brighter*, *equally bright* or less bright than before?	
Reasoning:		
c)	(2 points) Switch I is now open again. Switch II is closed: Does bulb C glow *brighter*, *equally bright* or less bright than in Question a)? Which of the four bulbs glows brightest?	
Reasoning:		

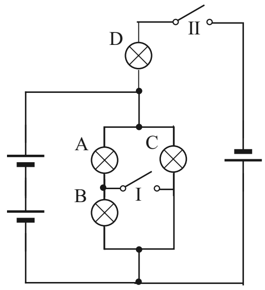
Exam in EE1ME, February 7th, 2012, Task 1, English translation

E.4 QUIZ IN EE2EE, JULY 18TH, 2012

Matrikelnummer: ____________________

☐ Ich habe an der ET2-Projektwoche teilgenommen.

Aufgabe 1



Alle Batterien in der nebenstehenden Schaltung sind identisch und können als ideale Spannungsquellen aufgefasst werden. Der lange dünne Strich bezeichnet jeweils den Pluspol der Batterie. Die vier Lampen sind ebenfalls identisch und für alle auftretenden Spannungen ausreichend dimensioniert. Bei identischen Lampen ist die Helligkeit ein Indikator für sowohl Spannung als auch Strom.

Die Schalter I und II sind anfänglich beide geöffnet, wie im Bild dargestellt.

a. Ordnen Sie die Lampen A, B, C und D nach ihrer Helligkeit (bei geöffneten Schaltern). Falls zwei Lampen gleich hell sind oder eine Lampe gar nicht leuchtet, geben Sie dies ausdrücklich an.

Begründen Sie kurz.

b. Schalter I wird nun geschlossen. Schalter II bleibt weiterhin offen.

- Leuchtet Lampe A nach Schließen von Schalter I *heller, gleich hell* oder *weniger hell* als zuvor?

  ☐ heller ☐ gleich hell ☐ weniger hell
- Leuchtet Lampe C nach Schließen von Schalter I *heller, gleich hell* oder *weniger hell* als zuvor?

  ☐ heller ☐ gleich hell ☐ weniger hell

Begründen Sie jeweils kurz.

c. Schalter I wird nun wieder geöffnet. Schalter II wird geschlossen.

- Leuchtet Lampe C nach Schließen von Schalter II *heller, gleich hell* oder *weniger hell* als in der Ausgangssituation (Aufgabenteil a)?

  ☐ heller ☐ gleich hell ☐ weniger hell
- Welche der vier Lampen leuchtet nun am hellsten?

  ☐ A ☐ B ☐ C ☐ D

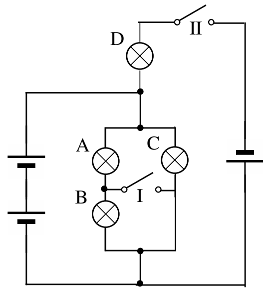
Begründen Sie kurz.

Quiz in EE2EE, July 18th, 2012, page 1, German original

Matriculation Number: ____________________

☐ I participated in the EE2EE project week.

Task 1



The circuit at right contains identical batteries, which can be treated as ideal voltage sources. The long, thin line indicates the positive terminal of the respective battery. The four bulbs are identical. All occurring voltages are within operating range of the bulbs. The brightness of ideal bulbs is an indicator for their voltage as well as their current.

The switches I and II are open at the beginning, as shown in the picture.

a. Rank the bulbs A, B, C, and D by their brightness (with both switches open). State explicitly, if two bulbs glow equally bright or a bulb does not glow at all.

Briefly explain your reasoning.

b. Switch I gets closed now. Switch II stays open.

- Does bulb A glow *brighter*, *equally bright*, or *dimmer*, after switch I has been closed?
  ☐ brighter ☐ equally bright ☐ dimmer
- Does bulb C glow *brighter*, *equally bright*, or *dimmer*, after switch I has been closed?
  ☐ brighter ☐ equally bright ☐ dimmer

Briefly explain your answers.

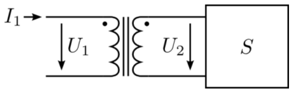
c. Switch I is opened again. Switch II is closed.

- Compared to Task 1.a, does bulb C glow *brighter*, *equally bright*, or *dimmer* after closing switch II?
  ☐ brighter ☐ equally bright ☐ dimmer
- Which of the four bulbs glows brightest?
  ☐ A ☐ B ☐ C ☐ D

Briefly explain your answer.

Quiz in EE2EE, July 18th, 2012, page 1, English translation

Aufgabe 2



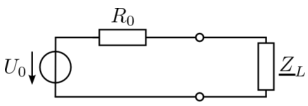
Auf der Sekundärseite eines idealen Übertragers soll eine Scheinleistung von 1kVA bereitgestellt werden. Bestimmen Sie daraus für den Strom auf der Primärseite, wenn die Spannung auf der Primärseite einen Effektivwert von U_1 = 40V hat und die der Sekundärseite einen Effektivwert von U_2 = 10V?

Kreuzen Sie das richtige Ergebnis an:

☐ I_1=1,57A ☐ I_1=6,25A ☐ I_1=25A ☐ I_1=40A ☐ I_1=100A ☐ I_1=400A

Begründen Sie kurz.

Aufgabe 3



Gegeben ist der Schaltkreis links mit idealer Wechselspannungsquelle U_0 und Innenwiderstand R_0. Die Lastimpedanz $\underline{Z}_L$ wird nun betragsmäßig vergrößert.

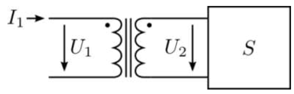
Nimmt die in R_0 umgesetzte Verlustleistung *zu*, *nimmt sie ab* oder *bleibt sie gleich*? Falls *keine Aussage möglich* ist, kreuzen Sie das entsprechende Feld an:

☐ nimmt zu ☐ bleibt gleich ☐ nimmt ab ☐ keine Aussage möglich

Begründen Sie kurz.

Quiz in EE2EE, July 18th, 2012, page 2, German original

Task 2



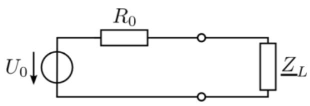
An apparent power of 1kVA is to be provided on the secondary side of an ideal transformer. Determine from this for the current [sic] on the primary side, if the voltage on the primary side has an RMS value of V_1= 40V and the voltage on the secondary side has an RMS value of V_2 = 10V?

Check the correct result:

☐ I_1=1,57A ☐ I_1=6,25A ☐ I_1=25A ☐ I_1=40A ☐ I_1=100A ☐ I_1=400A

Explain briefly.

Task 3



The circuit at left contains an ideal AC voltage source V_0 and an internal resistance R_0. The load impedance $\underline{Z}_L$ is now increased in terms of amount.

Does the power loss in R_0 *increase*, *decreases* or *remain the same*? If no statement is possible, check the appropriate box:

☐ increase ☐ remain the same ☐ decrease ☐ no statement possible

Explain briefly.

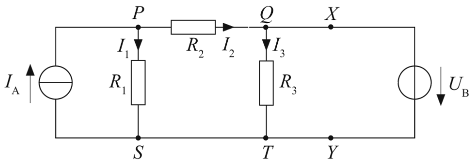
Quiz in EE2EE, July 18th, 2012, page 2, English translation

E.5 QUIZ IN EE1ME, JANUARY 14TH, 2013

Grundlagen der Elektrotechnik I **QUIZ**

Studiengang: ______

1. Die Schaltung rechts enthält eine Stromquelle I_A, eine Spannungsquelle U_B, sowie die Widerstände R_1 bis R_3. I_1 und U_1 bezeichnen den Strom in bzw. die Spannung an R_1, u.s.w. Die Werte von I_A und U_B können als positiv angenommen werden.



Der Wert des Quellenstroms I_A wird nun erhöht. Geben Sie an, welche der folgenden Größen sich dadurch ändern und welche nicht.

Bitte *begründen* Sie jeweils kurz Ihre Antwort.

a. U_3 ☐ ändert sich ☐ ändert sich nicht
Begründung:

b. I_3 ☐ ändert sich ☐ ändert sich nicht
Begründung:

c. U_1 ☐ ändert sich ☐ ändert sich nicht
Begründung:

c. I_1 ☐ ändert sich ☐ ändert sich nicht
Begründung:

c. U_2 ☐ ändert sich ☐ ändert sich nicht
Begründung:

d. I_2 ☐ ändert sich ☐ ändert sich nicht
Begründung:

Bitte beachten Sie die weiteren Aufgaben auf der Rückseite!

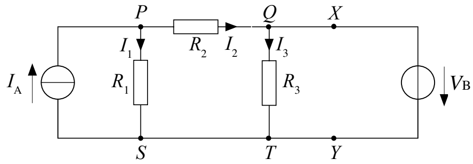
kautz@tu-harburg.de Winter 2012/2013

Quiz in EE1ME, January 14th, 2013, page 1, German original

Fundamental of Electrical Engineering I **QUIZ**

Study program: ____

1. The circuit at right contains a current source I_A, a voltage source V_B, and the resistances R_1 to R_3. I_1 and V_1 denote the current and the voltage at R_1, etc. The values of I_A and V_B are positive.



The value of the source current I_A is now increased. For each of the following quantities, state if its value changes or stays the same.

Please give a short *explanation* of your answer.

a. V_3 ☐ changes ☐ stays the same
Reasoning:

b. I_3 ☐ changes ☐ stays the same
Reasoning:

c. V_1 ☐ changes ☐ stays the same
Reasoning:

c. I_1 ☐ changes ☐ stays the same
Reasoning:

c. V_2 ☐ changes ☐ stays the same
Reasoning:

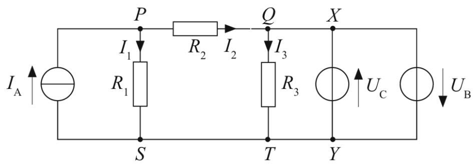
d. I_2 ☐ changes ☐ stays the same
Reasoning:

Please turn the page!

kautz@tu-harburg.de Winter 2012/2013

Quiz in EE1ME, January 14th, 2013, page 1, English translation

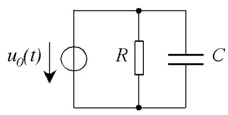
2. In der Schaltung aus Aufgabe 1 soll zwischen den Punkten X und Y nun eine weitere Spannungsquelle U_C so eingesetzt werden, dass ihr Zählpfeil im Bild nach oben zeigt.



a. Welche Werte darf U_C annehmen, wenn sich die Ströme in den Widerständen R_1 bis R_3 ***nicht ändern sollen?*** Wenn dies für keinen Wert von U_C möglich ist, geben Sie dies ausdrücklich an. Begründen Sie kurz Ihre Antwort.

b. Welche Werte darf U_C annehmen, wenn sich die Ströme in den Widerständen R_1 bis R_3 ***beliebig ändern dürfen?*** Wenn dies für keinen Wert von U_C möglich ist, geben Sie dies ausdrücklich an. Begründen Sie kurz Ihre Antwort.

3. Die Schaltung rechts enthält eine ideale Wechselspannungsquelle $u_0(t)$ mit $u_0(t) = \hat{u}_0 \cdot \cos(\omega t + \varphi_0)$, sowie einen Widerstand R und eine Kapazität C. Die an den Bauteilen anliegenden Spannungen werden mit $u_R(t)$ und $u_C(t)$ bezeichnet; die entsprechenden Ströme mit $i_R(t)$ und $i_C(t)$. Der durch die Spannungsquelle fließende Strom werde mit $i_0(t)$ bezeichnet.



Zwei sinusförmige Signale haben die gleiche Phase, wenn sie ihre Maximalwerte (bei entsprechend gewähltem Vorzeichen) zu gleichen Zeitpunkten erreichen.

Tritt in den nachfolgenden Teilaufgaben zwischen den jeweils genannten Signalen eine Phasenverschiebung auf oder haben die beiden Signale die gleiche Phase?

Bitte *begründen* Sie jeweils kurz Ihre Antwort.

a. $u_R(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

b. $u_C(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

c. $i_R(t)$ und $i_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

d. $i_0(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

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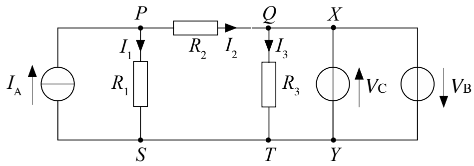
Quiz in EE1ME, January 14th, 2013, page 2, German original

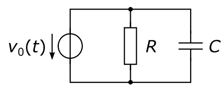
2. In the circuit from task 1, a new voltage source V_C shall be added between the nodes X and Y. The arrow indicating the direction of the voltage shall point upwards, as shown in the picture.



   a. Which values may V_C take, so that the currents through the resistors R_1 to R_3 ***stay the same?*** State explicitly, if this is not possible for any value of V_C. Briefly explain your reasoning.

   b. Which values may V_C take, if the currents through the resistors R_1 to R_3 ***may change?*** State explicitly, if this is not possible for any value of V_C. Briefly explain your reasoning.

3. The circuit at right contains an ideal AC voltage source $v'_0(t) = \hat{v}'_0 \cos(\ t + {}_0)$, a resistance R and a capacitance C. The voltages across the components are denoted by $v_R(t)$ and $v(t)$; the corresponding currents are $i_R(t)$ and $i_C(t)$. The current through the source is denoted by $i_0(t)$.



   Two sinusoidal signals are in phase if they reach their maxima (with the same sign) at the same time.

   Is there a phase shift between the signals listed below or are they in phase?

   Please, briefly *explain* your reasoning.

   a. $v_R(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
   Explanation:

   b. $v_C(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
   Explanation:

   c. $i_R(t)$ and $i_0(t)$ ☐ phase shift ☐ in phase
   Explanation:

   d. $i_0(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
   Explanation:

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Quiz in EE1ME, January 14th, 2013, page 2, English translation

E.6 EXAM IN EE1ME, FEBRUARY 27TH, 2013

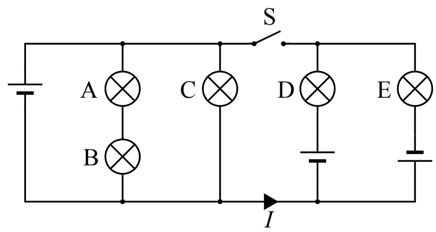
Klausur 27.02.2013 „Grundlagen der Elektrotechnik I“ (MB, SB, EUT, LUM, VT, BVT) Seite 1 von 3

Vorname: **Nachname:**

Matr.-Nr.:

Aufgabe 1 (8 Punkte)

Alle Batterien in der nebenstehenden Schaltung sind identisch und können als ideale Spannungsquellen betrachtet werden. Der lange Strich bezeichnet jeweils den Pluspol der Batterie. Die fünf Lampen sind ebenfalls identisch und für alle auftretenden Spannungen ausreichend dimensioniert.



Zunächst ist der Schalter **S geöffnet**.	
a)	(2 Punkte) Ordnen Sie die Lampen A, B, C, D und E nach ihrer Helligkeit. Falls zwei Lampen gleich hell sind oder eine Lampe gar nicht leuchtet, geben Sie dies ausdrücklich an. Begründen Sie kurz.
b)	(1 Punkt) Ist der eingezeichnete Strom I größer, kleiner oder gleich Null? Begründen Sie kurz.
Nun wird der Schalter **S geschlossen**.	
c)	(3 Punkte) Ordnen Sie die Lampen A, B, C, D und E nach ihrer Helligkeit. Falls zwei Lampen gleich hell sind oder eine Lampe gar nicht leuchtet, geben Sie dies ausdrücklich an. Begründen Sie kurz.
d)	(1 Punkt) Ist die Lampe C nach Schließen des Schalters S heller, gleich hell oder weniger hell als vor Schließen des Schalters. Begründen Sie kurz.
e)	(1 Punkt) Ist die Lampe E nach Schließen des Schalters S heller, gleich hell oder weniger hell als vor Schließen des Schalters. Begründen Sie kurz.

Technische Universität Hamburg-Harburg, Institut für Elektrische Energiesysteme und Automation
Prof. Dr.-Ing. G. Ackermann, Eißendorfer Str. 38, 21073 Hamburg

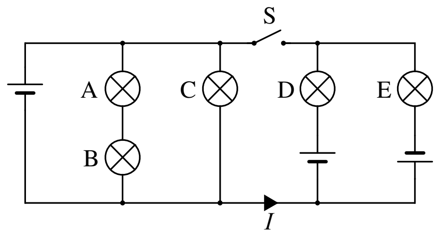
Exam in EE1ME, February 27th, 2013, Task 1, German original

First name: **Last name:**

Matriculation number:

Problem 1 (8 points)

The circuit at right contains identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery. The five bulbs are also identical and all occurring voltages are within operating range of the bulbs.



Switch **S** is **open**.	
a)	(2 points) Rank bulbs A, B, C, D, and E by their brightness. State explicitly, if two bulbs are equally bright or a bulb does not glow at all. Briefly explain your reasoning.
b)	(1 points) Is current I (indicated in the picture) larger than, less than or equal to zero? Briefly explain your reasoning.
Switch **S** is **closed** now.	
c)	(3 points) Rank bulbs A, B, C, D, and E by their brightness. State explicitly, if two bulbs are equally bright or a bulb does not glow at all. Briefly explain your reasoning.
d)	(1 point) Is bulb C brighter, equally bright or less bright than before the closing of switch S? Briefly explain your reasoning.
e)	(1 point) Is bulb E brighter, equally bright or less bright than before the closing of switch S. Briefly explain your reasoning.

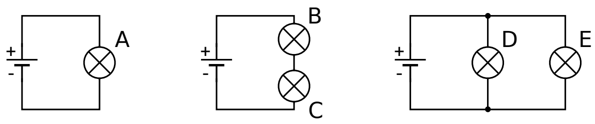
Exam in EE1ME, February 27th, 2013, Task 1, English translation

E.7 QUIZ IN EE2EE, APRIL 3RD, 2013

Matrikelnummer: ___________________

Aufgabe 1

Die folgenden drei Stromkreise bestehen aus identischen Glühlampen und identischen, idealen Batterien. (Nehmen Sie an, dass die Batterien ideale Spannungsquellen sind, d. h. ihr Innenwiderstand ist Null.)



Sortieren Sie die fünf Glühlampen A bis E entsprechend ihrer Helligkeit.

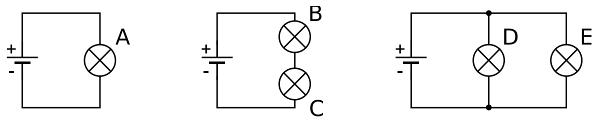
Begründen Sie kurz.

Bitte beachten Sie die Rückseite!

Quiz in EE2EE, April 3rd, 2013, page 1, German original

Problem 1

The three circuits underneath contain identical bulbs and identical ideal batteries. (Assume that the batteries are ideal voltage sources, i.e. they have no internal resistance.)



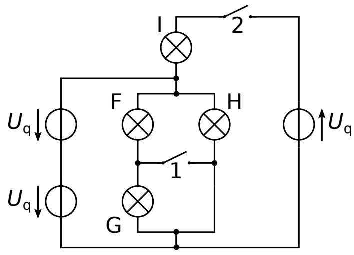
Rank the 5 bulbs by their brightness.

Briefly explain your reasoning.

Please turn the page!

Quiz in EE2EE, April 3rd, 2013, page 1, English translation

Aufgabe 2



Alle drei Gleichspannungsquellen in der nebenstehenden Schaltung haben die identische Spannung U_q und können als ideale Quellen aufgefasst werden. Die vier Lampen sind ebenfalls identisch und für alle auftretenden Spannungen ausreichend dimensioniert. (Bei identischen Lampen ist die Helligkeit ein Indikator für sowohl Spannung als auch Strom.)

Die Schalter 1 und 2 sind anfänglich beide geöffnet, wie im Bild dargestellt.

a. Ordnen Sie die Lampen F, G, H und I nach ihrer Helligkeit (bei geöffneten Schaltern). Falls zwei Lampen gleich hell sind oder eine Lampe gar nicht leuchtet, geben Sie dies ausdrücklich an.

Begründen Sie kurz.

b. Schalter 1 wird nun geschlossen. Schalter 2 bleibt weiterhin offen.

- Leuchtet Lampe F nach Schließen von Schalter 1 *heller, gleich hell* oder *weniger hell* als zuvor?
  ☐ heller ☐ gleich hell ☐ weniger hell
- Leuchtet Lampe H nach Schließen von Schalter 1 *heller, gleich hell* oder *weniger hell* als zuvor?
  ☐ heller ☐ gleich hell ☐ weniger hell

Begründen Sie jeweils kurz.

Lampe F:

Lampe H:

c. Schalter 1 wird nun wieder geöffnet. Schalter 2 wird geschlossen.

- Leuchtet Lampe H nach Schließen von Schalter 2 *heller, gleich hell* oder *weniger hell* als in der Ausgangssituation (Aufgabenteil a)?
  ☐ heller ☐ gleich hell ☐ weniger hell
- Ordnen Sie die Lampen F, G, H und I erneut nach ihrer Helligkeit. Falls zwei Lampen gleich hell sind oder eine Lampe gar nicht leuchtet, geben Sie dies ausdrücklich an.

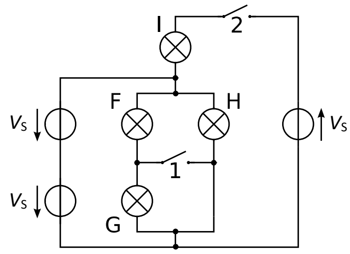
Begründen Sie jeweils kurz.

Lampe H:

Ordnung:

Quiz in EE2EE, April 3rd, 2013, page 2, German original

Problem 2



The three DC voltage sources in the circuit at right are ideal voltage sources with the source voltage V_S. The four bulbs are also identical and all occurring voltages are within their operating range. (The brightness of ideal bulbs is an indicator for their voltage and current.)

The switches 1 and 2 are open in the beginning as indicated in the figure.

a. Rank the bulbs F, G, H, and I by their brightness (switches are open). State explicity, if two bulbs are equally bright or a bulb does not glow at all.

Briefly explain your reasoning.

b. Switch 1 is closed now. Switch 2 stays open.

- Does bulb F glow *brighter*, *equally bright*, or *dimmer* than before the closing of switch 1?

  ☐ brighter ☐ equally bright ☐ dimmer

- Does bulb H glow *brighter*, *equally bright*, or *dimmer* than before the closing of switch 1?

  ☐ brighter ☐ equally bright ☐ dimmer

Briefly explain each answer.

Bulb F:

Bulb H:

c. Switch 1 is opened now. Switch 2 is closed.

- Does bulb H glow *brighter*, *equally bright*, or *dimmer* compared to the situation in part a?

  ☐ brighter ☐ equally bright ☐ dimmer

- Rank the bulbs F, G, H, and I by their brightness (switches are open). State explicity, if two bulbs are equally bright or a bulb does not glow at all.

Briefly explain each answer.

Bulb H:

Ranking:

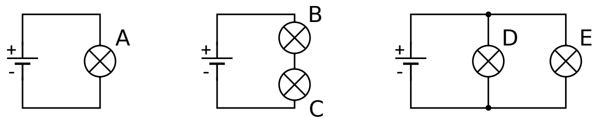
Quiz in EE2EE, April 3rd, 2013, page 2, English translation

E.8 QUIZ IN EE2EE, JULY 15TH, 2013

Matrikelnummer: ____________________

Aufgabe 1

Die folgenden drei Stromkreise bestehen aus identischen Glühlampen und identischen, idealen Batterien. (Nehmen Sie an, dass die Batterien ideale Spannungsquellen sind, d. h. ihr Innenwiderstand ist Null.)



Sortieren Sie die fünf Glühlampen A bis E entsprechend ihrer Helligkeit. (Bitte verwenden Sie hierzu die Vergleichsoperatoren „>“, „<“ und „=“.)

Begründen Sie kurz.

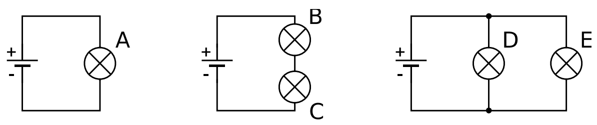
Bitte beachten Sie die Rückseite!

Quiz in EE2EE, July 15th, 2013, version A, page 1, German original

Matriculation number: ____________________

Task 1

The three circuits beneath contain identical bulbs and identical, ideal batteries. (Assume that the batteries are ideal voltage sources, i.e. they have no internal resistance.)



Rank the five bulbs A through E by their brightness.
(Please use the relational operators '>', '<', and '='.)

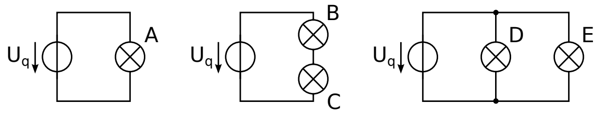
Explain briefly.

Please turn the page!

Matrikelnummer: ____________________

Aufgabe 1

Die folgenden drei Stromkreise bestehen aus identischen Glühlampen und identischen Spannungquellen.



Sortieren Sie die fünf Glühlampen A bis E entsprechend ihrer Helligkeit. (Bitte verwenden Sie hierzu die Vergleichsoperatoren „>“, „<“ und „=“.)

Begründen Sie kurz.

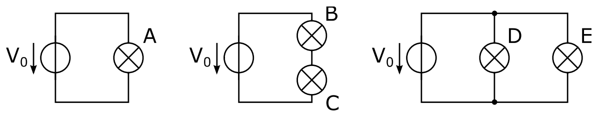
Bitte beachten Sie die Rückseite!

Quiz in EE2EE, July 15th, 2013, version B, page 1, German original

Matriculation Number: ____________________

Task 1

The three circuits beneath contain identical bulbs and identical voltage sources.



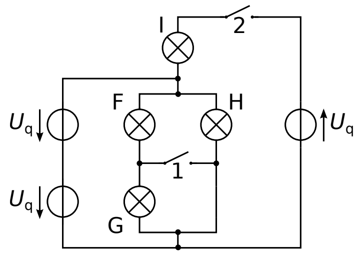
Rank the five bulbs A through E by their brightness.
(Please use the relational operators '>', '<', and '='.)

Explain briefly.

Please note the reverse side!

Quiz in EE2EE, July 15th, 2013, version B, page 1, English translation

Aufgabe 2



Alle drei Gleichspannungsquellen in der nebenstehenden Schaltung haben die identische Spannung U_q und können als ideale Quellen aufgefasst werden. Die vier Lampen sind ebenfalls identisch und für alle auftretenden Spannungen ausreichend dimensioniert. (Bei identischen Lampen ist die Helligkeit ein Indikator für sowohl Spannung als auch Strom.)

Die Schalter 1 und 2 sind anfänglich beide geöffnet, wie im Bild dargestellt.

a. Ordnen Sie die Lampen F, G, H und I nach ihrer Helligkeit (bei geöffneten Schaltern). Falls zwei Lampen gleich hell sind oder eine Lampe gar nicht leuchtet, geben Sie dies ausdrücklich an.

Begründen Sie kurz.

b. Schalter 1 wird nun geschlossen. Schalter 2 bleibt weiterhin offen.

- Leuchtet Lampe F nach Schließen von Schalter 1 *heller, gleich hell* oder *weniger hell* als zuvor?

  ☐ heller ☐ gleich hell ☐ weniger hell
- Leuchtet Lampe H nach Schließen von Schalter 1 *heller, gleich hell* oder *weniger hell* als zuvor?

  ☐ heller ☐ gleich hell ☐ weniger hell

Begründen Sie jeweils kurz.

Lampe F:

Lampe H:

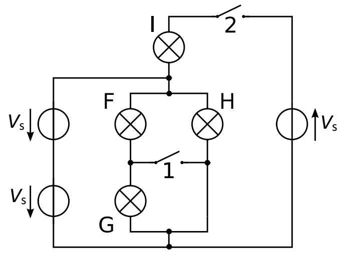
c. Beschreiben Sie, wie die Lampen F, G und H verschaltet sind. (Reihenschaltung, Parallelschaltung, etc.)

- Wenn Schalter 1 geschlossen und Schalter 2 geöffnet ist:

- Wenn Schalter 1 geöffnet und Schalter 2 geöffnet ist:

Quiz in EE2EE, July 15th, 2013, versions A&B, page 2, German original

Problem 2



The three DC voltage sources in the circuit at right are ideal voltage sources with the source voltage V_s. The four bulbs are also identical and all occurring voltages are within their operating range. (The brightness of ideal bulbs is an indicator for their voltage and current.)

The switches 1 and 2 are open in the beginning, as indicated at right.

a. Rank the bulbs F, G, H, and I by their brightness (switches are open). State explicitly, if two bulbs are equally bright or a bulb does not glow at all.

Briefly explain your reasoning.

b. Switch 1 is closed now. Switch 2 stays open.

- Does bulb F glow *brighter*, *equally bright* or *dimmer* than before the closing of switch 1?

  ☐ brighter ☐ equally bright ☐ dimmer

- Does bulb H glow *brighter*, *equally bright* or *dimmer* than before the closing of switch 1?

  ☐ brighter ☐ equally bright ☐ dimmer

Briefly explain each answer.

Bulb F:

Bulb H:

c. Describe how bulbs F, G, and H are connected. (series connection, parallel connection, etc.)

- When switch 1 closed and switch 2 open:

- When switch 1 open and switch 2 closed:

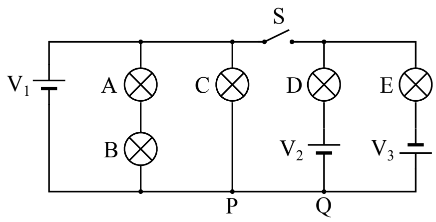
Quiz in EE2EE, July 15th, 2013, versions A&B, page 2, English translation

E.9 Quiz in EE3EE, October 24th, 2013

Eingangstest Netzwerktheorie

Matrikelnummer: ________________
Meine Übung ist am ☐Mo ☐Mi ☐Fr

Alle Batterien in der nebenstehenden Schaltung sind identisch und können als ideale Spannungsquellen betrachtet werden. Der lange Strich bezeichnet jeweils den Pluspol der Batterie. Die fünf Lampen sind ebenfalls identisch und für alle auftretenden Spannungen ausreichend dimensioniert.



Schalter **S** ist zunächst **geöffnet**.

a. Ordnen Sie die Lampen **C, D** und **E** nach ihrer Helligkeit. Falls zwei Lampen gleich hell sind oder eine Lampe gar nicht leuchtet, geben Sie dies ausdrücklich an.

Begründen Sie kurz.

b. Vergleichen sie die elektrischen Potentiale $\phi(P)$ und $\phi(Q)$ an den Punkten P und Q.
☐ $\phi(P) > \phi(Q)$ ☐ $\phi(P) = \phi(Q)$ ☐ $\phi(P) < \phi(Q)$ ☐ lässt sich nicht entscheiden

Begründen Sie kurz.

Schalter **S** wird nun **geschlossen**.

c. Ordnen Sie die Lampen **C, D** und **E** nach ihrer Helligkeit. Falls zwei Lampen gleich hell sind oder eine Lampe gar nicht leuchtet, geben Sie dies ausdrücklich an.

Begründen Sie kurz.

d. Ist die Lampe C nach Schließen des Schalters S *heller*, *gleich hell* oder *weniger hell* als vor Schließen des Schalters.
☐ heller ☐ gleich hell ☐ weniger hell

Begründen Sie kurz.

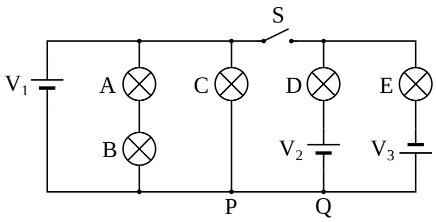
Bitte beachten Sie die Rückseite!

Quiz in EE3EE, October 24th, 2013, version A, page 1, German original

Pre-Test EE3EE

Matriculation number: ______________
Recitation section: ☐Mon ☐Wed ☐Fri

The circuit at right contains identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery. All five bulbs are identical and all occurring voltages are within the operating range of the bulbs.



Initially, Switch **S is open**.

a. Rank the bulbs **C**, **D**, and **E** by their brightness. State explicitly, if two bulbs glow equally bright, or a bulb does not light up at all.

Briefly explain your reasoning.

b. Compare the electric potentials $\phi(P)$ and $\phi(Q)$ of nodes P and Q.

☐ $\phi(P) > \phi(Q)$ ☐ $\phi(P) = \phi(Q)$ ☐ $\phi(P) < \phi(Q)$ ☐ cannot be decided

Briefly explain your reasoning.

Now, Switch **S is closed**.

c. Rank bulbs **C**, **D**, and **E** by their brightness. State explicitly, if two bulbs glow equally bright, or a bulb does not light up at all.

Briefly explain your reasoning.

d. Does bulb C glow *brighter*, *equally bright* or *less bright* than before closing the switch S?

☐ brighter ☐ equally bright ☐ less bright

Briefly explain your reasoning.

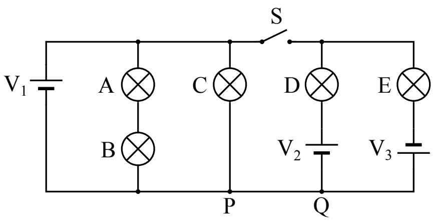
Please turn the page!

Quiz in EE3EE, October 24th, 2013, version A, page 1, English translation

Eingangstest Netzwerktheorie

Matrikelnummer: ________________
Meine Übung ist am ☐Mo ☐Mi ☐Fr

Alle Batterien in der nebenstehenden Schaltung sind identisch und können als ideale Spannungsquellen betrachtet werden. Der lange Strich bezeichnet jeweils den Pluspol der Batterie. Die fünf Lampen sind ebenfalls identisch und für alle auftretenden Spannungen ausreichend dimensioniert.



Schalter **S** ist zunächst **geöffnet**.

a. Ordnen Sie die Lampen **C, D** und **E** nach ihrer Helligkeit. Falls zwei Lampen gleich hell sind oder eine Lampe gar nicht leuchtet, geben Sie dies ausdrücklich an.

Begründen Sie kurz.

b. Fließt zwischen den Punkten P und Q ein positiver elektrischer Strom?
☐ ja, von P nach Q ☐ ja, von Q nach P ☐ nein ☐ lässt sich nicht entscheiden

Begründen Sie kurz.

Schalter **S** wird nun **geschlossen**.

c. Ordnen Sie die Lampen **C, D** und **E** nach ihrer Helligkeit. Falls zwei Lampen gleich hell sind oder eine Lampe gar nicht leuchtet, geben Sie dies ausdrücklich an.

Begründen Sie kurz.

d. Ist die Lampe C nach Schließen des Schalters S *heller*, *gleich hell* oder *weniger hell* als vor Schließen des Schalters.
☐ heller ☐ gleich hell ☐ weniger hell

Begründen Sie kurz.

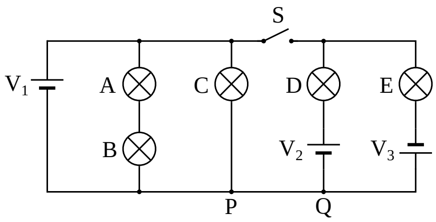
Bitte beachten Sie die Rückseite!

Quiz in EE3EE, October 24th, 2013, version B, page 1, German original

Pre-Test EE3EE

Matriculation number: ______________
Recitation section: ☐Mon ☐Wed ☐Fri

The circuit at right contains identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery. All five bulbs are identical and all occurring voltages are within the operating range of the bulbs.



Initially, Switch **S is open**.

a. Rank the bulbs **C**, **D**, and **E** by their brightness. State explicitly, if two bulbs glow equally bright, or a bulb does not light up at all.

Briefly explain your reasoning.

a. Does a positive electric current flow between nodes P and Q?

☐ yes, from P to Q ☐ yes, from Q to P ☐ no ☐ cannot be decided

Briefly explain your reasoning.

Now, Switch **S is closed**.

b. Rank bulbs **C**, **D**, and **E** by their brightness. State explicitly, if two bulbs glow equally bright, or a bulb does not light up at all.

Briefly explain your reasoning.

c. Does bulb C now glow *brighter*, *equally bright* or *less bright* than before closing the switch S?

☐ brighter ☐ equally bright ☐ less bright

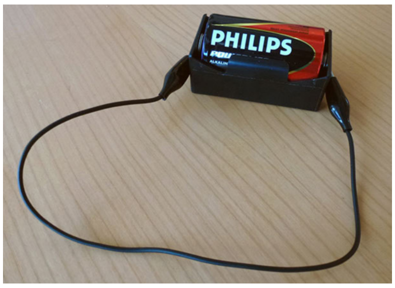
Briefly explain your reasoning.

Please turn the page!

Quiz in EE3EE, October 24th, 2013, version B, page 1, English translation

Das nebenstehende Bild zeigt eine handelsübliche Batterie (Mono-Zelle, 1,5V) sowie ein Verbindungskabel mit Krokodilklemmen.
Die beiden Enden des Kabels sind mit je einem Pol der Batterie verbunden worden.

Zeichnen Sie ein Ersatzschaltbild für die beschriebene Situation unter Verwendung der üblichen Symbole. Benennen Sie jedes Element erläutern Sie Ihr Ersatzschaltbild kurz.



Ersatzschaltbild

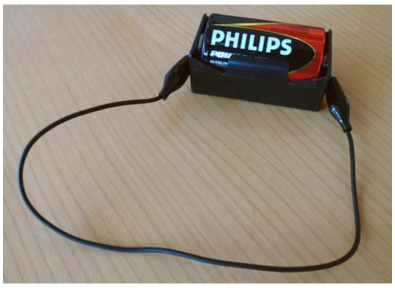
Erläuterungen

Vielen Dank!

Quiz in EE3EE, October 24th, 2013, versions A&B, page 2, German original

The picture at right shows a standard battery (mono-cell, 1.5V) and a wire with alligator clips. A student connects each end of the wire with one of the terminals of the battery.

Draw a circuit diagram (equivalent circuit diagram) for the described situation using the usual symbols.



Equivalent Circuit Diagram

Explanations

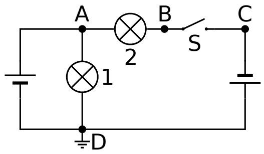
Thank you!

Quiz in EE3EE, October 24th, 2013, versions A&B, page 2, English translation

E.10 QUIZ IN EE1ME, JANUARY 13TH, 2014

Grundlagen der Elektrotechnik I **QUIZ** Studiengang: _____________
Matrikelnummer: _____________

1. Die Schaltung rechts enthält zwei identische Batterien, die als ideale Spannungsquellen betrachtet werden können. Der kurze Strich kennzeichnet den Minus-Pol der Batterie, der lange Strich den Pluspol. Das Symbol an Punkt D gibt an, dass das Potential dort gleich Null ist. Die Lampen 1 und 2 sind ebenfalls identisch, der Schalter S ist zunächst geöffnet.



Bei offenem Schalter:

a. Sortieren Sie die drei Spannungen U_{AB}, U_{AC} U_{AD} nach ihrem Betrag. Verwenden Sie hierfür die Vergleichsoperatoren >, < und =. Sollten zwei Spannungen gleich groß oder eine Spannung gleich Null sein, geben Sie dies ausdrücklich an.
Antwort:

Begründung:

b. Sortieren Sie die Punkte A bis D nach ihrem elektrischen Potential ϕ_A bis ϕ_D.
Antwort:

Begründung:

Der Schalter wird nun geschlossen:

c. Leuchtet Lampe 1 nach Schließen des Schalters *heller*, *gleich hell* oder *weniger hell* als zuvor?
☐ heller ☐ gleich hell ☐ weniger hell ☐ Ich bin mir unsicher
Begründung:

d. Ist die Spannung U_{AC} nach Schließen des Schalters betragsmäßig *größer*, *gleich groß* oder *kleiner* als zuvor?
☐ größer ☐ gleich groß ☐ kleiner ☐ Ich bin mir unsicher
Begründung:

e. Geben Sie für jeden der Punkte an, ob sich das an ihm anliegende elektrische Potential beim Schließen des Schalters *ändert* oder *gleich bleibt*.

Punkt	**Potential ändert sich / ändert sich nicht**	***Begründung***
A		
B		
C		
D		

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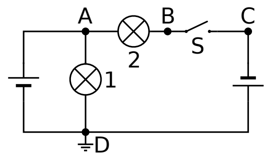
Quiz in EE1ME, January 13th, 2014, page 1, German original

Grundlagen der Elektrotechnik I **QUIZ** Studiengang: ____________
Matrikelnummer: ____________

1. The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery. The symbol at node D denotes zero potential. The bulbs 1 and 2 are also identical. Switch S is open at first.



Open switch:

a. Rank the three voltages V_{AB}, V_{AC} and V_{AD} by their absolute value. Use the relational operators '>', '<' and '='. State explicitly, if two voltages are equal or a voltage is zero.
Answer:

Reasoning:

b. Rank nodes A to D by their potential ϕ_A to ϕ_D.
Answer:

Explanation:

The switch gets closed now:

c. Does bulb 1 glow *brighter*, *equally bright* or *dimmer* than before the closing of the switch?

☐ brighter ☐ equally bright ☐ dimmer ☐ I am not sure.
Explanation:

d. Is the voltage V_{AC} *larger*, *the same* or *lower* than before the closing of the switch?
☐ higher ☐ the same ☐ lower ☐ I am not sure.
Explanation:

e. For each of the nodes A to D, state if the electric potential *does* or *does not* change when the switch is closed.

Node	**Potential does change / does not change**	***Explanation***
A		
B		
C		
D		

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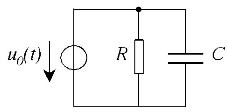
Quiz in EE1ME, January 13th, 2014, page 1, English translation

2. Die Schaltung rechts enthält eine ideale Wechselspannungsquelle $u_0(t)$ mit $u_0(t) = \hat{u}_0 \cdot \cos(\omega t + \varphi_0)$, sowie einen Widerstand R und eine Kapazität C. Die an den Bauteilen anliegenden Spannungen werden mit $u_R(t)$ und $u_C(t)$ bezeichnet; die entsprechenden Ströme mit $i_R(t)$ und $i_C(t)$. Der durch die Spannungsquelle fließende Strom werde mit $i_0(t)$ bezeichnet.



Zwei sinusförmige Signale haben die gleiche Phase, wenn sie ihre Maximalwerte (bei entsprechend gewähltem Vorzeichen) zu gleichen Zeitpunkten erreichen.

Tritt in den nachfolgenden Teilaufgaben zwischen den jeweils genannten Signalen eine Phasenverschiebung auf oder haben die beiden Signale die gleiche Phase?

Bitte *begründen* Sie jeweils stichwortartig Ihre Antwort.

a. $u_R(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

b. $u_C(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

c. $i_R(t)$ und $i_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

d. $i_0(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

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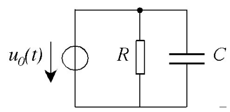
Quiz in EE1ME, January 13th, 2014, page 2, German original

2. The circuit at right contains a ideal AC voltage source $u_0(t) = \hat{u}_0 \cdot \cos(\omega t + \varphi_0)$, a resistance R and a capacitance C. The voltages across the components are denoted by $u_R(t)$ and $u_C(t)$; the corresponding currents are $i_R(t)$ und $i_C(t)$. The current through the source is denoted by $i_0(t)$.



2 sinusoidal signals are in phase if the reach their maxima (with the same sign) at the same time.

Is there a phase shift between the following signals or not?

Please explain your answers briefly.

a. $u_R(t)$ und $u_0(t)$ ☐ phase shift ☐ in phase
Explanation:

b. $u_C(t)$ und $u_0(t)$ ☐ phase shift ☐ in phase
Explanation:

c. $i_R(t)$ und $i_0(t)$ ☐ phase shift ☐ in phase
Explanation:

d. $i_0(t)$ und $u_0(t)$ ☐ phase shift ☐ in phase
Explanation:

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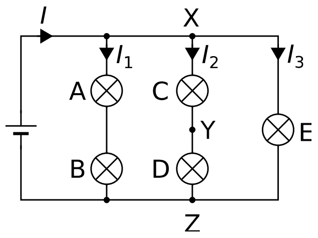
Quiz in EE1ME, January 13th, 2014, page 2, English translation

E.11 EXAM IN EE1ME, MARCH 11TH, 2014

Version B

Regel:
Durch Rundungsfehler und ähnliche Effekte kann es vorkommen, dass eine von Ihnen richtig berechnete Lösung nicht exakt als eine der Alternativen angegeben ist. Markieren Sie dann den Wert, der Ihrer Lösung am nächsten kommt.

Aufgabe 1 (8 Punkte)
Die Batterie in der nebenstehenden Schaltung kann als ideale Spannungsquelle betrachtet werden. Der lange Strich bezeichnet den Pluspol der Batterie. Die fünf Lampen sind identisch und für alle auftretenden Spannungen ausreichend dimensioniert.



Aufgabe 1.1 (1 Punkt)
Lampe A leuchtet...

Aufgabe 1.1	A	B	C	D	E
	heller als B	weniger hell als B	gleich hell wie B		

Aufgabe 1.2 (1 Punkt)
Lampe A leuchtet...

Aufgabe 1.2	A	B	C	D	E
	heller als C	weniger hell als C	gleich hell wie C		

Aufgabe 1.3 (1 Punkt)
Lampe A leuchtet...

Aufgabe 1.3	A	B	C	D	E
	heller als E	weniger hell als E	gleich hell wie E		

Nun wird Lampe D aus ihrer Fassung geschraubt.

Aufgabe 1.4 (1 Punkt)
Der Betrag der Spannung zwischen den Punkten X und Y, $|U_{XY}|$...

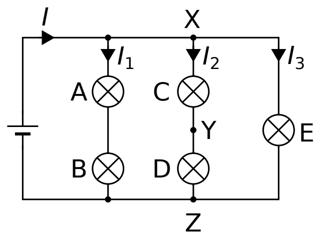
Aufgabe 1.4	A	B	C	D	E
	erhöht sich	bleibt gleich	verringert sich auf 0	verringert sich, jedoch nicht auf 0	

Exam in EE1ME, March 3rd, 2014, page 1, German original

Version B

Rule:
Due to rounding errors and similar effects, it can happen that a solution that you have correctly calculated is not listed exactly as one of the alternatives. In that case, select the value that comes closest to your solution.

Problem 1 (8 points)
The battery in the circuit at right can be treated as an ideal voltage source. The long line indicates the positive terminal of the battery. All five bulbs are identical and all occurring voltages are within the operating range of the bulbs.



Task 1.1 (1 point)
Bulb A glows…

Task 1.1	A	B	C	D	E
	brighter than B	less bright than B	equally bright as B		

Task 1.2 (1 point)
Bulb A glows…

Task 1.2	A	B	C	D	E
	brighter than C	less bright than C	equally bright as C		

Task 1.3 (1 point)
Bulb A glows…

Task 1.3	A	B	C	D	E
	brighter than E	less bright than E	equally bright as E		

Now, bulb D is removed from its socket.

Task 1.4 (1 point)
The absolute value of the voltage between nodes X and Y, $|U_{XY}|$,…

Task 1.4	A	B	C	D	E
	increases,	stays the same,	decreases to 0,	decreases, but not to 0.	

Exam in EE1ME, March 3rd, 2014, page 1, English translation

Aufgabe 1.5 (1 Punkt)
Der Betrag der Spannung zwischen den Punkten *Y* und *Z*, $|U_{YZ}|$...

Aufgabe 1.5	A	B	C	D	E
	erhöht sich	bleibt gleich	verringert sich auf 0	verringert sich, jedoch nicht auf 0	

Aufgabe 1.6 (1 Punkt)
Der Betrag des Batteriestroms, $|I|$...

Aufgabe 1.6	A	B	C	D	E
	erhöht sich	bleibt gleich	verringert sich auf 0	verringert sich, jedoch nicht auf 0	

Aufgabe 1.7 (1 Punkt)
Der Betrag des Stroms durch Lampen A und B, $|I_1|$...

Aufgabe 1.7	A	B	C	D	E
	erhöht sich	bleibt gleich	verringert sich auf 0	verringert sich, jedoch nicht auf 0	

Aufgabe 1.8 (1 Punkt)
Der Betrag des Stroms durch Lampe E, $|I_3|$...

Aufgabe 1.8	A	B	C	D	E
	erhöht sich	bleibt gleich	verringert sich auf 0	verringert sich, jedoch nicht auf 0	

Exam in EE1ME, March 3rd, 2014, page 2, German original

Task 1.5 (1 point)
The absolute value of the voltage between nodes Y and Z, $|U_{YZ}|$,…

Task 1.5	A	B	C	D	E
	increases,	stays the same,	decreases to 0,	decreases, but not to 0.	

Task 1.6 (1 point)
The absolute value of the current of the battery, $|I|$,…

Task 1.6	A	B	C	D	E
	increases,	stays the same,	decreases to 0,	decreases, but not to 0.	

Task 1.7 (1 point)
The absolute value of the current through bulbs A and B, $|I_1|$,…

Task 1.7	A	B	C	D	E
	increases,	stays the same,	decreases to 0,	decreases, but not to 0.	

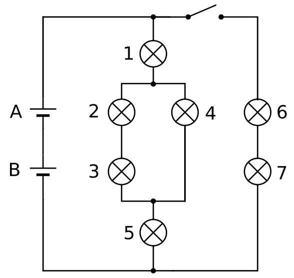
Task 1.8 (1 point)
The absolute value of the current through bulb E, $|I_3|$,…

Task 1.8	A	B	C	D	E
	increases,	stays the same,	decreases to 0,	decreases, but not to 0.	

Exam in EE1ME, March 3rd, 2014, page 2, English translation

E.12 QUIZ IN EE1ME, NOVEMBER 26TH, 2014

Aufgabe 1



Der folgende Stromkreis besteht aus den identischen Glühlampen 1 bis 7 und den identischen Batterien A und B. Die Batterien können als ideale Spannungsquellen betrachtet werden, d. h. ihr Innenwiderstand ist Null.

Der Schalter ist zunächst geöffnet.

1. Sortieren Sie die Glühlampen 1 bis 5 entsprechend ihrer Helligkeit. Verwenden Sie hierfür die Vergleichsoperatoren >, < und =. Sollte eine Lampe aus sein, geben Sie dies ausdrücklich an.

   Begründen Sie kurz.

2. Ist die Spannung an Lampe 1 *größer*, *kleiner*, oder *gleich* der an Lampe 5?
   ☐ größer ☐ kleiner ☐ gleich ☐ Ich bin mir unsicher

   Begründen Sie kurz.

3. Ist die Spannung an Lampe 6 *gleich* oder un*gleich* Null?
   ☐ gleich Null ☐ ungleich Null ☐ Ich bin mir unsicher

   Begründen Sie kurz.

Nun wird der Schalter geschlossen.

4. Ist nach Schließen des Schalter Lampe 1 *heller*, *dunkler*, oder *gleich hell* wie vorher?
   ☐ heller ☐ dunkler ☐ gleich hell ☐ Ich bin mir unsicher

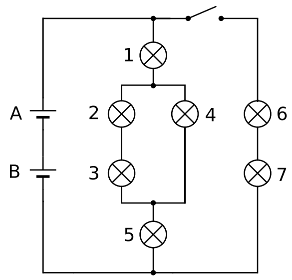
   Begründen Sie kurz.

Bitte beachten Sie die Rückseite!

Quiz in EE1ME, November 26th, 2014, page 1, German original

Task 1

The circuit at right contains the identical bulbs 1 to 7 and the identical batteries A and B. The batteries can be treated as ideal voltage sources, i.e. their internal resistance is zero.



At first, the switch is in the open position.

1. Rank bulbs 1 to 5 according to their brightness. Use the relational operators >, < and =. If a bulb does not glow at all, state this explicitly.

   Explain briefly.

2. Is the voltage across bulb 1 *higher*, *lower* or *the same* as the voltage across bulb 5?
   ☐ higher ☐ lower ☐ the same ☐ I am not sure

   Explain briefly.

3. Is the voltage across bulb 6 *equal* or *not equal* to zero?
   ☐ equal to zero ☐ not equal to zero ☐ I am not sure

   Explain briefly.

The switch is now closed.

4. Does bulb 1 glow *brighter*, *dimmer* or *equally bright* than before closing the switch?
   ☐ brighter ☐ dimmer ☐ equally bright ☐ I am not sure

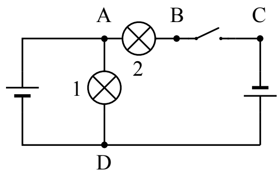
   Explain briefly.

Please turn the page!

Quiz in EE1ME, November 26th, 2014, page 1, English translation

Aufgabe 2

Die Schaltung rechts enthält zwei identische Batterien, die als ideale Spannungsquellen betrachtet werden können. Der kurze Strich kennzeichnet den Minus-Pol der Batterie. Die Lampen 1 und 2 sind identisch, der Schalter ist geöffnet.



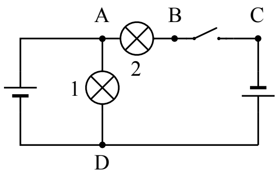
Bei offenem Schalter:

Sortieren Sie die Spannungen U_{AB}, U_{AC}, U_{AD} und U_{BC} nach ihrem Betrag. Sollten zwei Spannungen gleich groß oder eine Spannung gleich Null sein, geben Sie dies ausdrücklich an. Verwenden Sie die Vergleichsoperatoren >, < und =.

Begründen Sie kurz.

Quiz in EE1ME, November 26th, 2014, page 2, German original

Task 2



The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The short line denotes the negative terminal of the battery. The bulbs 1 and 2 are identical, the switch is open.

With the switch in the open position:

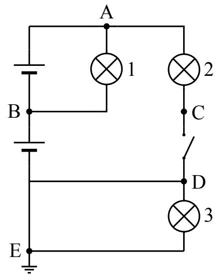
Rank the voltages V_{AB}, V_{AC}, V_{AD} and V_{BC} by their absolute value. If two voltages have the same absolute value or one voltage is zero, state this explicitly. Use the relational operators >, < and =.

Explain briefly.

E.13 QUIZ IN EE1ME, JANUARY 7TH, 2015

Grundlagen der Elektrotechnik I **QUIZ**

1. Die Schaltung rechts enthält zwei identische Batterien, die als ideale Spannungsquellen betrachtet werden können. Der lange Strich kennzeichnet die positive Klemme der Batterie, der kurze Strich die negative Klemme. Der Betrag der Spannung an einer einzelnen Batterie wird als U_{Batt} bezeichnet. Die Glühlampen 1 bis 3 sind ebenfalls identisch, an Punkt E ist eine Erdung angeschlossen.



Der Schalter ist zunächst geöffnet.

a. Ordnen Sie die Spannungen U_{AB}, U_{AC}, U_{AD} und U_{CD} nach ihrem Betrag. Verwenden Sie dafür die Vergleichsoperatoren >, < und =. Wenn zwei Spannungen gleich groß oder eine Spannung gleich Null ist, geben Sie dies ausdrücklich an.

Antwort:

Begründung

b. Sortieren Sie die Punkte A bis E nach ihrem elektrischen Potential Φ_{A} bis Φ_{E}.

Antwort:

Begründung:

Der Schalter wird nun geschlossen.

c. Ist die Spannung U_{AD} nach Schließen des Schalters *größer*, *gleich groß* oder *kleiner* als zuvor?

☐ größer ☐ gleich groß ☐ kleiner ☐ Ich bin mir unsicher

Begründung:

d. Wie groß ist die Spannung U_{AC} nach Schließen des Schalters?

☐ Null ☐ kleiner als U_{Batt}, aber nicht null ☐ U_{Batt} ☐ größer als U_{Batt}

Begründung:

e. Wie ändert sich die Helligkeit der Lampen nach Schließen des Schalters? Begründen Sie jeweils.

Lampe 1 ist nach Schließen des Schalters ☐ heller ☐ gleich hell ☐ dunkler als zuvor.	***Begründung:***
Lampe 2 ist nach Schließen des Schalters ☐ heller ☐ gleich hell ☐ dunkler als zuvor.	***Begründung:***
Lampe 3 ist nach Schließen des Schalters ☐ heller ☐ gleich hell ☐ dunkler als zuvor.	***Begründung:***

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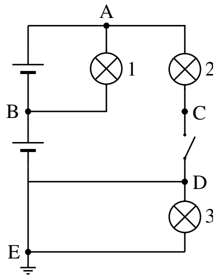
Quiz in EE1ME, January 7th, 2015, page 1, German original

Fundamentals of Electrical Engineering I **QUIZ**



1. The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery, the short line the negative terminal. V_{Batt} denotes the absolute value of the voltage across a single battery. Bulbs 1 to 3 are identical, node E is connected to ground.

At first, the switch is in the open position.

a. Rank the voltages V_{AB}, V_{AC}, V_{AD}, and V_{CD} by their absolute value. Use the relational operators >, < and =. If two voltages have the same absolute value or one voltage is zero, state this explicitly.
Answer:

Explanation:

b. Rank nodes A to E by their electric potentials Φ_A to Φ_E.
Answer:

Explanation:

The switch is closed now.

c. Is voltage V_{AD} *higher*, *equally high* or *lower* than before closing the switch?
☐ higher ☐ equally high ☐ lower ☐ I am not sure
Explanation:

d. What is the value of voltage V_{AC} after closing the switch?
☐ zero ☐ smaller than V_{Batt}, but not zero ☐ V_{Batt} ☐ larger than V_{Batt}
Explanation:

e. How does the brightness of the bulbs change after closing the switch? Explain your reasoning.

Bulb 1 is ☐ brighter ☐ equally bright ☐ dimmer than before closing the switch.	***Explanation:***
Bulb 2 is ☐ brighter ☐ equally bright ☐ dimmer than before closing the switch.	***Explanation:***
Bulb 3 is ☐ brighter ☐ equally bright ☐ dimmer than before closing the switch.	***Explanation:***

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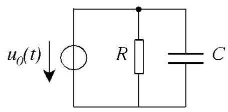
Quiz in EE1ME, January 7th, 2015, page 1, English translation

2. Die Schaltung rechts enthält eine ideale Wechselspannungsquelle $u_0(t)$ mit $u_0(t) = \hat{u}_0 \cos(\omega t + \varphi_0)$, sowie einen Widerstand R und eine Kapazität C. Die an den Bauteilen anliegenden Spannungen werden mit $u_R(t)$ und $u_C(t)$ bezeichnet; die entsprechenden Ströme mit $i_R(t)$ und $i_C(t)$. Der durch die Spannungsquelle fließende Strom werde mit $i_0(t)$ bezeichnet.



Zwei sinusförmige Signale haben die gleiche Phase, wenn sie ihre Maximalwerte (bei entsprechend gewähltem Vorzeichen) zu gleichen Zeitpunkten erreichen.

Tritt in den nachfolgenden Teilaufgaben zwischen den jeweils genannten Signalen eine Phasenverschiebung auf oder haben die beiden Signale die gleiche Phase?

Bitte *begründen* Sie jeweils stichwortartig Ihre Antwort.

a. $u_R(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

b. $u_C(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

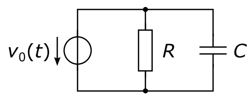
c. $i_R(t)$ und $i_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

d. $i_0(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

dion.timmermann@tuhh.de Winter 2014/2015

Quiz in EE1ME, January 7th, 2015, page 2, German original

2. The circuit at right contains an ideal AC voltage source $v_0(t) = \hat{v}_0 \cos(\omega t+\varphi_0)$, a resistance R, and a capacitance C. The voltages over the components are denoted by $v_R(t)$ and $v_C(t)$; the corresponding currents are $i_R(t)$ and $i_C(t)$. The current through the source is denoted by $i_0(t)$.



Two sinusoidal signals are in phase if they reach their maxima (with the same sign) at the same time.

Is there a phase shift between the following signals or are they in phase?

Please *explain* your answers shortly.

a. $v_R(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
Explanation:

b. $v_C(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
Explanation:

c. $i_R(t)$ and $i_0(t)$ ☐ phase shift ☐ in phase
Explanation:

d. $i_0(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
Explanation:

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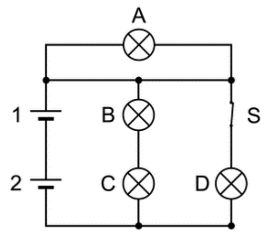
Quiz in EE1ME, January 7th, 2015, page 2, English translation

E.14 EXAM IN EE1ME, FEBRUARY 3RD, 2015

Regel:
Durch Rundungsfehler und ähnliche Effekte kann es vorkommen, dass eine von Ihnen richtig berechnete Lösung nicht exakt als eine der Alternativen angegeben ist. Markieren Sie dann den Wert, der Ihrer Lösung am nächsten kommt.

Aufgabe 1
Die Batterien 1 und 2 in der nebenstehenden Schaltung sind identisch und können als ideale Spannungsquellen betrachtet werden. Der lange Strich bezeichnet den Pluspol der jeweiligen Batterie. Die vier Lampen sind identisch und für alle auftretenden Spannungen ausreichend dimensioniert.



Aufgabe 1.1, 1,2 (2 Punkte, wenn beide Antworten richtig)
Schalter S ist geschlossen

Lampe B ist

	A	B	C	D	E
Aufgabe 1.1	aus (d. h. leuchtet nicht),	dunkler als Lampe C, aber nicht aus,	gleich hell wie Lampe C,	heller als Lampe C,	

weil

	A	B	C	D	E
Aufgabe 1.2	Strom von Lampe B verbraucht wird.	der gleiche Strom durch beide fließt.	ein Teil der Spannung an Lampe B abfällt.	Lampe C ein niedrigeres Potential hat als Lampe B.	die Elek-tronen zu-erst durch Lampe C fließen.

Aufgabe 1.3, 1,4 (2 Punkte, wenn beide Antworten richtig)

Schalter S ist geschlossen

Lampe C ist

	A	B	C	D	E
Aufgabe 1.3	aus (d. h. leuchtet nicht),	dunkler als Lampe D, aber nicht aus,	gleich hell wie Lampe D,	heller als Lampe D,	

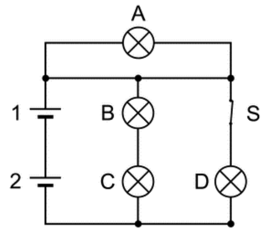
weil

	A	B	C	D	E
Aufgabe 1.4	an Lampe C eine geringere Spannung anliegt.	Lampe B parallel zu Lampe D ist.	der Strom den Weg des geringsten Widerstands nimmt.	sich der Strom gleichmäßig aufteilt.	Lampe C näher an den Batterien ist.

Exam in EE1ME, February 3rd, 2015, page 1, German original

Rule:
Due to rounding errors and similar effects, it can happen that a solution that you have correctly calculated is not listed exactly as one of the alternatives. In that case, select the value that comes closest to your solution.

Task 1
The batteries 1 and 2 in the circuit at right are identical and they can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery. All four bulbs are identical and all occurring voltages are within their operating ranges.



Task 1.1, 1,2 (2 points, if both answers are correct)

Switch S is closed.

Bulb B is

	A	B	C	D	E
Task 1.1	off (i.e. does not glow),	dimmer than bulb C, but not off,	equally bright as bulb C,	brighter than bulb C,	

because

	A	B	C	D	E
Task 1.2	current is consumed in bulb B.	the same current flows through both.	part of the voltage drops at bulb B.	bulb C has a lower potential than bulb B.	the electrons flow through bulb C first.

Task 1.3, 1,4 (2 points, if both answers are correct)

Switch S is closed.

Bulb C is

	A	B	C	D	E
Task 1.3	off (i.e. does not glow),	dimmer than bulb D, but not off,	equally bright as bulb D,	brighter than bulb D,	

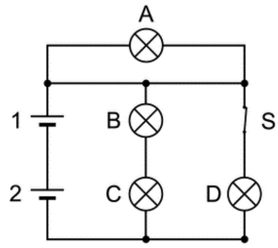
because

	A	B	C	D	E
Task 1.4	there is a smaller voltage across bulb C.	bulb B is parallel to bulb D.	the current takes the path of least resistance.	the current splits equally.	bulb C is closer to the batteries.

Exam in EE1ME, February 3rd, 2015, page 1, English translation

Aufgabe 1.5, 1,6 (2 Punkte, wenn beide Antworten richtig)

Schalter S ist geschlossen



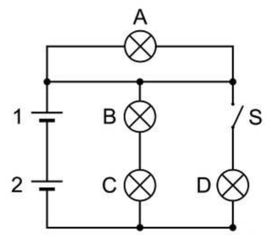
Lampe A ist

	A	B	C	D	E
Aufgabe 1.5	aus (d.h. leuchtet nicht),	dunkler als Lampe D, aber nicht aus,	gleich hell wie Lampe D,	heller als Lampe D,	

weil

	A	B	C	D	E
Aufgabe 1.6	sie sich die Spannung mit den Lampen B, C und D teilt.	sie in einem geschlossenen Stromkreis ist.	sie mit keiner der anderen Lampen parallel geschaltet ist.	in Kabeln Verluste auftreten.	keine Spannung an ihr anliegt.

Aufgabe 1.7, 1,8 (2 Punkte, wenn beide Antworten richtig)
Nun wird Schalter S geöffnet



Die Spannung an Lampe D ist

	A	B	C	D	E
Aufgabe 1.7	gleich 0,	zwischen 0 und der Spannung *einer* Batterie	gleich der Spannung *einer* Batterie	größer als die Spannung *einer* Batterie	

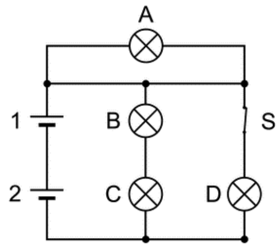
weil

	A	B	C	D	E
Aufgabe 1.8	$U = R \bullet I$ nur bei ge-schlossenen Kreisen gilt.	durch sie kein Strom fließt.	sie parallel zu den Batterien ist.	an offenen Schaltern keine Span-nung an-liegt.	bei offenen Schaltern Spannung anliegen kann.

Exam in EE1ME, February 3rd, 2015, page 2, German original

Problem 1.5, 1,6 (2 points, if both answers are correct)

Switch S is closed.



Bulb A is

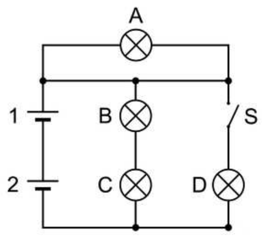
	A	B	C	D	E
Task 1.5	off (i.e. does not glow),	dimmer than bulb D, but not off,	equally bright as bulb D,	brighter than bulb D,	

because

	A	B	C	D	E
Task 1.6	it shares its voltage with bulbs B, C, and D.	it is in a closed circuit.	it is not parallel to any other bulb.	there are losses in the wires.	there is no voltage across it.

Problem 1.7, 1,8 (2 points, if both answers are correct)

Now, switch S is open.



The voltage across bulb D is

	A	B	C	D	E
Task 1.7	equal to 0,	between 0 and the voltage of *one* battery,	equal to the voltage of *one* battery,	larger than the voltage of *one* battery,	

because

	A	B	C	D	E
Task 1.8	$V = R \cdot I$ is only valid in closed circuits.	there is no current through bulb D.	bulb D is parallel to the batteries.	there is no voltage across open switches.	there can be a voltage across open switches.

Exam in EE1ME, February 3rd, 2015, page 2, English translation

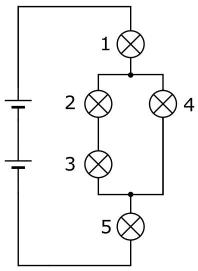
E.15 QUIZ IN EE1ME, NOVEMBER 10TH, 2015

Zuordnungscode

☐☐	1. und 2. Buchstabe des Vornamens deiner Mutter
☐☐	Eigener Geburtstag (Tag des Monats)
☐☐	1. und 2. Buchstabe des Vornamens deines Vaters
☐☐	Anzahl älterer (nicht jüngerer!) Brüder
☐☐	Anzahl älterer (nicht jüngerer!) Schwestern
☐☐	1. und 2. Buchstabe deines des Geburtsorts
☐☐	Vorletzte und letzte Ziffer des eigenen Geburtsjahres

Aufgabe 1

Der Stromkreis rechts besteht aus identischen Glühlampen und idealen Batterien. (Nehmen Sie an, dass die Batterien ideale Spannungsquellen sind, d. h. ihr Innenwiderstand ist Null.)



a) Sortieren Sie die Lampen nach ihrer Helligkeit. Sollten zwei Lampen gleich hell oder eine Lampe gar nicht leuchten, geben Sie dies ausdrücklich an. Verwenden Sie die Vergleichsoperatoren >, < und =.

Begründen Sie kurz.

b) Die Ströme durch die Lampen 1, 3 und 4 werden mit einem Messgerät gemessen. Sie sollen im folgenden als I_1, I_3 und I_4 bezeichnet werden. In welcher Beziehung stehen sie?

☐ $I_1 < I_3 + I_4$
☐ $I_1 > I_3 + I_4$
☐ $I_1 = I_3 = I_4$
☐ $I_1 = I_3 + I_4$
☐ Ich bin mir unsicher.

Begründen Sie kurz.

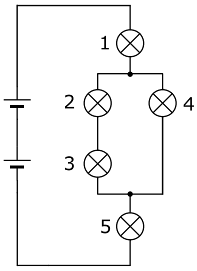
Bitte beachten Sie die Rückseite!

Test in EE1ME, November 10th, 2015, page 1, version A, German original

Identification Code

- 1. and 2. letter of your mother's first name
- Your day of birth (day of the month)
- 1. and 2. letter of your father's first name
- Number of older (not younger!) brothers
- Number of older (not younger!) sisters
- 1. and 2. letter of your place of birth
- second but last and last digit of your year of birth

Task 1



The circuit at right contains identical bulbs and ideal batteries. (The batteries can be treated as ideal voltage sources, i.e. their internal resistance is zero.)

a) Rank all bulbs by their brightness. If two bulbs glow equally bright or a bulb does not glow at all, state this explicitly. Use the relational operators >, <, and =.

Explain briefly.

b) The currents through bulbs 1, 3, and 4 are measured using a current meter. The currents are denoted by I_1, I_3, and I_4, respectively. What is their relation?

- ☐ $I_1 < I_3 + I_4$
- ☐ $I_1 = I_3 = I_4$
- ☐ I am not sure.
- ☐ $I_1 > I_3 + I_4$
- ☐ $I_1 = I_3 + I_4$

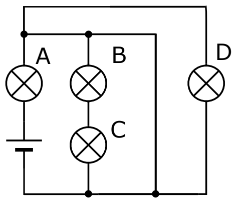
Explain briefly.

Please turn the page!

Test in EE1ME, November 10th, 2015, page 1, version A, English translation

Aufgabe 2

Der rechts abgebildete Stromkreis besteht aus identischen Glühlampen und einer Batterie, die als ideale Spannungsquelle betrachtet werden kann.



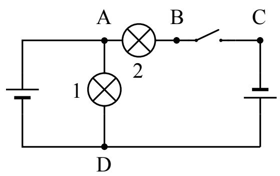
a) Zu welchen Lampen ist Lampe A parallel geschaltet?
Zu welchen ist sie in Reihe geschaltet? Beschreiben Sie.

b) Sortieren Sie die Lampen nach ihrer Helligkeit. Sollten zwei Lampen gleich hell oder eine Lampe gar nicht leuchten, geben Sie dies ausdrücklich an. Verwenden Sie die Vergleichsoperatoren >, < und =.

Begründen Sie kurz.

Aufgabe 3

Die Schaltung rechts enthält zwei identische Batterien, die als ideale Spannungsquellen betrachtet werden können. Der kurze Strich kennzeichnet den Minus-Pol der Batterie. Die Lampen 1 und 2 sind identisch, der Schalter ist geöffnet.



Bei offenem Schalter:

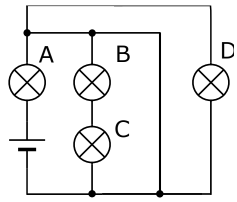
Sortieren Sie die Spannungen U_{AB}, U_{AC}, U_{AD} und U_{BC} nach ihrem Betrag. Sollten zwei Spannungen gleich groß oder eine Spannung gleich Null sein, geben Sie dies ausdrücklich an. Verwenden Sie die Vergleichsoperatoren >, < und =.

Begründen Sie kurz.

Vielen Dank!

Test in EE1ME, November 10th, 2015, page 2, German original

Task 2



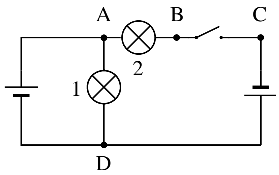
The circuit at the right contains identical bulbs and a battery, which can be treated as an ideal voltage source.

a) To which bulbs is bulb A connected in parallel?
To which ones is it connected in series? Describe briefly.

b) Rank the bulbs by their brightness. If two bulbs glow equally bright or a bulb does not glow at all, state this explicitly. Use the relational operators >, <, and =.

c) Explain briefly.

Task 3



The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The short line denotes the negative terminal of the battery. Bulbs 1 and 2 are identical, the switch is open.

With the switch in the open position:

Rank the voltages V_{AB}, V_{AC}, V_{AD}, and V_{BC} by their absolute value. If two voltages have the same absolute value or one voltage is zero, state this explicitly. Use the relational operators >, <, and =.

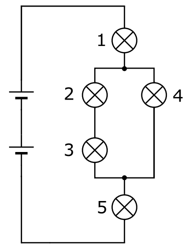
Explain briefly.

Thank you!

Test in EE1ME, November 10th, 2015, page 2, English translation

E.16 QUIZ IN EE1EE, NOVEMBER 26TH, 2015

Aufgabe 1



Der Stromkreis rechts besteht aus identischen Glühlampen und idealen Batterien. (Nehmen Sie an, dass die Batterien ideale Spannungsquellen sind, d. h. ihr Innenwiderstand ist Null.)

a) Sortieren Sie die Lampen nach ihrer Helligkeit. Sollten zwei Lampen gleich hell oder eine Lampe gar nicht leuchten, geben Sie dies ausdrücklich an. Verwenden Sie die Vergleichsoperatoren >, < und =.

Begründen Sie kurz.

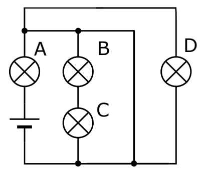
b) Die Ströme durch die Lampen 1, 3 und 4 werden mit einem Messgerät gemessen. Sie sollen im folgenden als I_1, I_3 und I_4 bezeichnet werden. In welcher Beziehung stehen sie?

☐ $I_1 < I_3 + I_4$ ☐ $I_1 = I_3 = I_4$ ☐ Ich bin mir unsicher.

☐ $I_1 > I_3 + I_4$ ☐ $I_1 = I_3 + I_4$

Begründen Sie kurz.

Aufgabe 2



Der rechts abgebildete Stromkreis besteht aus identischen Glühlampen und einer Batterie, die als ideale Spannungsquelle betrachtet werden kann.

a) Zu welchen Lampen ist Lampe A parallel geschaltet?
Zu welchen ist sie in Reihe geschaltet? Beschreiben Sie.

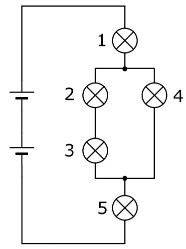
b) Sortieren Sie die Lampen nach ihrer Helligkeit. Sollten zwei Lampen gleich hell oder eine Lampe gar nicht leuchten, geben Sie dies ausdrücklich an. Verwenden Sie die Vergleichsoperatoren >, < und =.

Begründen Sie kurz.

Bitte beachten Sie auch die Rückseite!

Test in EE1EE, November 26th, 2015, page 1, German original

Task 1



The circuit at right contains identical bulbs and ideal batteries. (Assume that the batteries can be treated as ideal voltage sources, i.e. their internal resistance is zero.)

a) Rank all bulbs by their brightness. If two bulbs glow equally bright or a bulb does not glow at all, state this explicitly. Use the relational operators >, <, and =.

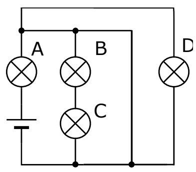
Explain briefly.

b) The currents through bulbs 1, 3, and 4 are measured using a current meter. The currents are denoted by I_1, I_3, and I_4, respectively. What is their relation?

- ☐ $I_1 < I_3 + I_4$
- ☐ $I_1 > I_3 + I_4$
- ☐ $I_1 = I_3 = I_4$
- ☐ $I_1 = I_3 + I_4$
- ☐ I am not sure.

Explain briefly.

Task 2



The circuit at right contains identical bulbs and a battery, which can be treated as an ideal voltage source.

a) To which bulbs is bulb A connected in parallel?
To which ones is it connected in series? Describe briefly.

b) Rank the bulbs by their brightness. If two bulbs glow equally bright or a bulb does not glow at all, state this explicitly. Use the relational operators >, <, and =.

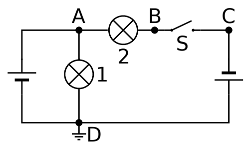
Explain briefly.

Please turn the page!

Test in EE1EE, November 26th, 2015, page 1, English translation

Aufgabe 3

Die Schaltung rechts enthält zwei identische Batterien, die als ideale Spannungsquellen betrachtet werden können. Der lange Strich kennzeichnet den Plus-Pol der Batterie. Die Glühlampen 1 und 2 sind ebenfalls identisch, an Punkt D ist eine Erdung angeschlossen.



Der Schalter ist geöffnet.

a) Sortieren Sie die Spannungen U_{AB}, U_{AC}, U_{AD} und U_{CD} nach ihrem Betrag. Verwenden Sie dafür die Vergleichsoperatoren >, < und =. Wenn zwei Spannungen gleich groß oder eine Spannung gleich Null ist, geben Sie dies ausdrücklich an.

Begründen Sie kurz.

b) Sortieren Sie die Punkte A bis E nach ihrem elektrischen Potential Φ_A bis Φ_E.

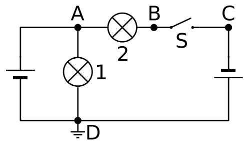
Begründen Sie kurz

Vielen Dank!

Test in EE1EE, November 26th, 2015, page 2, German original

Task 3

The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The long line denotes the positive terminal of the battery. Bulbs 1 and 2 are identical, the switch is open, point D is connected to ground.



The switch is open.

c) Rank the voltages V_{AB}, V_{AC}, V_{AD}, und V_{CD} by their absolute value. Use the relational operators >, <, and =. If two voltages are equally large or a voltage is zero, state this explicitly.

Explain briefly.

a) Rank points A to E by their electric potential Φ_A to Φ_E.

Explain briefly.

Thank you!

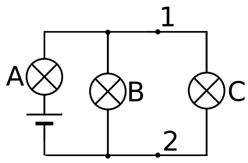
E.17 QUIZ IN EE1ME, DECEMBER 1ST, 2015

Zuordnungscode

- ☐☐ 1. und 2. Buchstabe des Vornamens deiner Mutter
- ☐☐ Eigener Geburtstag (Tag des Monats)
- ☐☐ 1. und 2. Buchstabe des Vornamens deines Vaters
- ☐☐ Anzahl älterer (nicht jüngerer!) Brüder
- ☐☐ Anzahl älterer (nicht jüngerer!) Schwestern
- ☐☐ 1. und 2. Buchstabe deines Geburtsorts
- ☐☐ Vorletzte und letzte Ziffer des eigenen Geburtsjahres

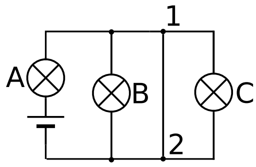
Aufgabe 1

Die rechtsstehende Schaltung besteht aus einer idealen Batterie und 3 identischen Lampen.



a) Sortieren Sie die Lampen A, B und C nach ihrer Helligkeit. Verwenden Sie die Vergleichsoperatoren >, < und =. Sollten zwei Lampen gleich hell sein oder eine Lampe nicht leuchten, geben Sie dies ausdrücklich an.

Begründen Sie.



b) Nun werden die Punkte 1 und 2 durch einen idealen Leiter verbunden. Verändert sich die Helligkeit der einzelnen Lampen im Vergleich zu vorher? Geben Sie Ihre Antwort für jede der Lampen A, B und C an. Bitte begründen Sie zusätzlich.

Lampe A ist nach Einfügen des idealen Leiters im Vergleich zu vorher: ☐ heller ☐ gleich hell ☐ dunkler, aber sie leuchtet noch ☐ dunkler und sie leuchtet nicht mehr	Begründung:
Lampe B ist nach Einfügen des idealen Leiters im Vergleich zu vorher: ☐ heller ☐ gleich hell ☐ dunkler, aber sie leuchtet noch ☐ dunkler und sie leuchtet nicht mehr	Begründung:
Lampe C ist nach Einfügen des idealen Leiters im Vergleich zu vorher: ☐ heller ☐ gleich hell ☐ dunkler, aber sie leuchtet noch ☐ dunkler und sie leuchtet nicht mehr	Begründung:

Bitte beachten Sie auch die Rückseite!

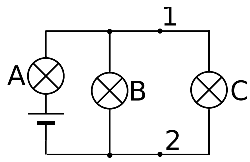
Test in EE1ME, December 1st, 2015, page 1, version A, German original

Identification Code

- 1. and 2. letter of your mother's first name
- Your day of birth (day of the month)
- 1. and 2. letter of your father's first name
- Number of older (not younger!) brothers
- Number of older (not younger!) sisters
- 1. and 2. letter of your place of birth
- Second but last and last digit of your year of birth

Task 1

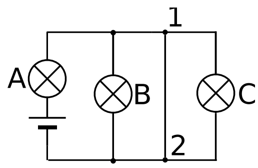
The circuit at the right contains an ideal battery and 3 identical bulbs.



a) Rank the bulbs A, B, and C by their brightness. Use the relational operators >, <, and =. State explicitly, if two bulbs are equally bright or a bulb does not glow at all.

Explain your reasoning.

b) Points 1 and 2 are now connected with an ideal conductor. Does the brightness of the individual bulbs change in comparison to before? State your answer for each of the bulbs A, B, and C. Please also explain your reasoning.

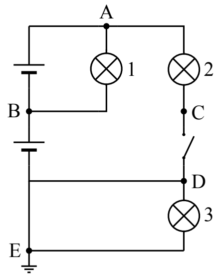


Compared to before the insertion of the ideal conductor, bulb A now is: ☐ brighter ☐ equally bright ☐ darker, but still glowing ☐ darker and does not glow anymore	Explanation:
Compared to before the insertion of the ideal conductor, bulb B now is: ☐ brighter ☐ equally bright ☐ darker, but still glowing ☐ darker and does not glow anymore	Explanation:
Compared to before the insertion of the ideal conductor, bulb C now is: ☐ brighter ☐ equally bright ☐ darker, but still glowing ☐ darker and does not glow anymore	Explanation:

Please turn the page!

Test in EE1ME, December 1st, 2015, page 1, version A, English translation

Aufgabe 2



Die Schaltung rechts enthält zwei identische Batterien, die als ideale Spannungsquellen betrachtet werden können. Der lange Strich kennzeichnet die positive Klemme der Batterie, der kurze Strich die negative Klemme. Die Glühlampen 1 bis 3 sind ebenfalls identisch, an Punkt E ist eine Erdung angeschlossen.

Der Schalter ist geöffnet.

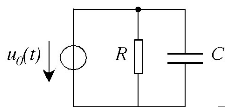
a. Ordnen Sie die Spannungen U_{AB}, U_{AC}, U_{AD} und U_{CD} nach ihrem Betrag. Verwenden Sie dafür die Vergleichsoperatoren >, < und =. Wenn zwei Spannungen gleich groß oder eine Spannung gleich Null ist, geben Sie dies ausdrücklich an.

Begründen Sie kurz.

b. Sortieren Sie die Punkte A bis E nach ihrem elektrischen Potential Φ_A bis Φ_E. Verwenden Sie dafür die Vergleichsoperatoren >, < und =. Wenn zwei Potentiale gleich groß oder ein Potentiale gleich Null ist, geben Sie dies ausdrücklich an.

Begründen Sie kurz.

Aufgabe 3



Die Schaltung rechts enthält eine ideale Wechselspannungsquelle $u_0(t)$ mit $u_0(t) = \hat{u}_0 \cos(\omega t + \varphi_0)$, sowie einen Widerstand R und eine Kapazität C. Die an den Bauteilen anliegenden Spannungen werden mit $u_R(t)$ und $u_C(t)$ bezeichnet; die entsprechenden Ströme mit $i_R(t)$ und $i_C(t)$. Der durch die Spannungsquelle fließende Strom werde mit $i_0(t)$ bezeichnet.

Zwei sinusförmige Signale haben die gleiche Phase, wenn sie ihre Maximalwerte (bei entsprechend gewähltem Vorzeichen) zu gleichen Zeitpunkten erreichen.

Tritt in den nachfolgenden Teilaufgaben zwischen den jeweils genannten Signalen eine Phasenverschiebung auf oder haben die beiden Signale die gleiche Phase?

Bitte *begründen* Sie jeweils stichwortartig Ihre Antwort.

a. $u_R(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

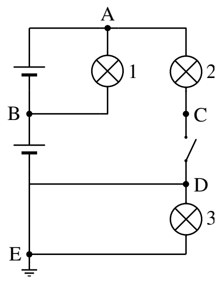
b. $u_C(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

c. $i_R(t)$ und $i_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

d. $i_0(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

Test in EE1ME, December 1st, 2015, page 2, German original

Task 2



The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery, the short line the negative terminal. Bulbs 1 to 3 are identical, node E is connected to ground.

The switch is in the open position.

a. Rank the voltages V_{AB}, V_{AC}, V_{AD}, and V_{CD} by their absolute value. Use the relational operators >, <, and =. If two voltages have the same absolute value or one voltage is zero, state this explicitly.

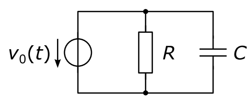
Briefly explain your reasoning.

b. Rank nodes A to E by their electric potential Φ_A to Φ_E. Use the relational operators >, <, and =. If two potentials have the same absolute value or one potential is zero, state this explicitly.

Briefly explain your reasoning.

Task 3

2. The circuit at right contains an ideal AC voltage source $v_0(t) = \hat{v}_0 \cos(\omega t + \varphi_0)$, a resistance R, and a capacitance C. The voltages over the components are denoted by $v_R(t)$ and $v_C(t)$; the corresponding currents are $i_R(t)$ and $i_C(t)$. The current through the source is denoted by $i_0(t)$.



Two sinusoidal signals are in phase if they reach their maxima (with the same sign) at the same time.

Is there a phase shift between the following signals or are they in phase?

Please *explain* your reasoning briefly.

a. $v_R(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
Explanation:

b. $v_C(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
Explanation:

c. $i_R(t)$ and $i_0(t)$ ☐ phase shift ☐ in phase
Explanation:

d. $i_0(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
Explanation:

E.18 EXAM IN EE1ME, FEBRUARY 2ND, 2016

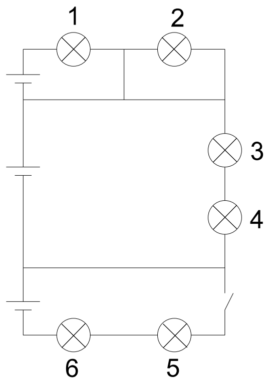
Klausur 02.02.2016 „Grundlagen der Elektrotechnik“ (PO ab WS 14/15)	Seite 1 von 10

Regel:
Bei allen Fragen ist jeweils genau eine Antwort richtig.
Durch Rundungsfehler und ähnliche Effekte kann es vorkommen, dass eine von Ihnen richtig berechnete Lösung nicht exakt als eine der Alternativen angegeben ist. Markieren Sie dann den Wert, der Ihrer Lösung am nächsten kommt.

Aufgabe 1

Die drei Batterien in der nebenstehenden Schaltung sind identisch und können als ideale Spannungsquellen betrachtet werden. Der lange Strich bezeichnet den Pluspol der jeweiligen Batterie. Die sechs Lampen sind identisch und für alle auftretenden Spannungen ausreichend dimensioniert.

Der Schalter ist geöffnet.



Aufgabe 1.1 (2 Punkte, wenn beide Antworten richtig)

Aufgabe 1.1.1	Lampe 2 ist
A	heller als Lampe 1
B	gleich hell wie Lampe 1
C	dunkler als Lampe 1, leuchtet aber noch
D	aus (leuchtet nicht)

Aufgabe 1.1.2	weil sie
A	in einem geschlossenen Stromkreis ist
B	sie kurzgeschlossen ist
C	sie in Reihe mit Lampe 1 geschaltet ist
D	Lampe 1 näher an den Batterien ist

Aufgabe 1.2 (2 Punkte, wenn beide Antworten richtig)

Aufgabe 1.2.1	Lampe 1 ist
A	dunkler als Lampe 3
B	gleich hell wie Lampe 3
C	heller als Lampe 3

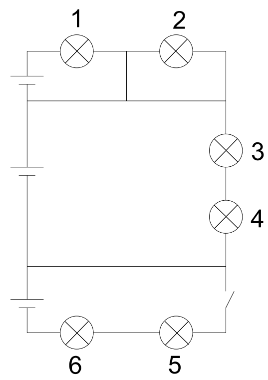
Aufgabe 1.2.2	weil
A	1 in Reihe mit 2 geschaltet ist und 3 in Reihe mit 4
B	die Spannung an Lampe 1 größer ist als an Lampe 3
C	die Spannung an Lampe 3 größer ist als an Lampe 1
D	sich die Spannung der beiden Batterien addiert
E	durch beide Batterien der gleiche Strom fließt

Exam in EE1ME, February 2nd, 2016, page 1, German original

Rule:
For each Task there is exactly one correct answer.
Due to rounding errors and similar effects, it can happen that a solution that you have correctly calculated is not listed exactly as one of the alternatives. In that case, select the value that comes closest to your solution.

Task 1
The three batteries in the circuit at right are identical and can be treated as ideal voltage sources. The long line indicates the positive terminal of a battery. All six bulbs are identical and all occurring voltages are within operating range of the bulbs.

The switch is open.



Task 1.1 (2 points, if both answers are correct)

Task 1.1.1	Bulbs 2 is
A	brighter than bulb 1
B	equally bright as bulb 1
C	less bright than bulb 1, but does glow
D	off (does not glow)

Task 1.1.2	because it
A	is in a closed circuit
B	is short-circuited
C	is in series with bulb 1
D	bulbs 1 is closer to the batteries

Task 1.2 (2 points, if both answers are correct)

Task 1.2.1	Bulbs 1 is
A	less bright than bulb 3
B	equally bright as bulb 3
C	brighter than bulb 3

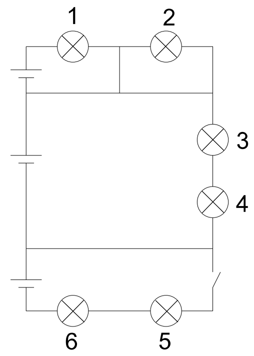
Task 1.2.2	because
A	1 is connected in series with 2 and 3 in series with 4
B	the voltage at bulb 1 is larger than at bulb 3
C	the voltage at bulb 3 is larger than at bulb 1
D	the voltages of both bulbs add up
E	the same current flows through both batteries

Exam in EE1ME, February 2nd, 2016, page 1, English translation

Aufgabe 1.3 (2 Punkte, wenn beide Antworten richtig)

Aufgabe 1.3.1	Durch Lampe 4 fließt
A	weniger Strom als durch Lampe 3
B	gleich viel Strom wie durch Lampe 3
C	mehr Strom als durch Lampe 3

Aufgabe 1.3.2	weil
A	sie in Reihe geschaltet sind
B	Lampe 3 Strom verbraucht
C	Lampe 4 Strom verbraucht
D	an 3 Spannung abfällt
E	beide Lampen identisch sind



gleiches Bild wie in Aufgabe 1.1

Aufgabe 1.4 (2 Punkte, wenn beide Antworten richtig)

Aufgabe 1.4.1	Die Spannung am Schalter ist
A	gleich 0 V
B	größer 0 V aber weniger als eine Batteriespannung
C	gleich einer Batteriespannung
D	größer einer Batteriespannung

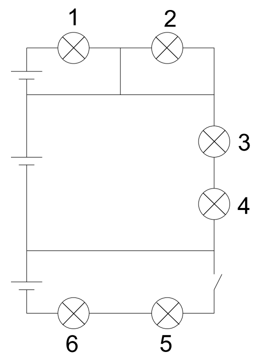
Aufgabe 1.4.2	weil
A	ohne Strom keine Spannung anliegen kann
B	an den Lampen 5 und 6 keine Spannung anliegt
C	$U = R \cdot I$ mit $I = 0$ A gilt
D	in der Schaltung drei Batterien enthalten sind
E	jeweils ein Drittel der Spannung an den Lampen 5 und 6 sowie dem Schalter abfällt

Exam in EE1ME, February 2nd, 2016, page 2, German original

Task 1.3 (2 points, if both answers are correct)

Task 1.3.1	Through bulb 4 flows
A	less current than through bulb 3
B	the same amount of current as through bulb 3
C	more current than through bulb 3

Task 1.3.2	because
A	they are connected in series
B	bulb 3 uses up some current
C	bulb 4 uses up some current
D	voltage drops across bulb 3
E	both bulbs are identical



same image as in Task 1.1

Task 1.4 (2 points, if both answers are correct)

Task 1.4.1	The voltage at the switch is
A	equal to 0 V
B	larger than 0 V but less than one battery voltage
C	equal to one battery voltage
D	larger than one battery voltage

Task 1.4.2	because
A	without current there can be no voltage
B	there is no voltage at bulbs 5 and 6
C	$V = R \cdot I$ applies with $I = 0$ A
D	there are three batteries in the circuit
E	a third of the voltage drops at each of the bulbs and the switch, respectively

E.19 QUIZ IN EE1ME, NOVEMBER 15TH, 2016

Zuordnungscode

☐☐ 1. und 2. Buchstabe des Vornamens der Mutter (z.B. SA für Sandra)

☐☐ Eigener Geburtstag (z.B. 07 für 7. Februar)

☐☐ 1. und 2. Buchstabe des Vornamens des Vaters (z.B. CH für Christian)

☐ Anzahl älterer (nicht jüngerer!) Brüder (z.B. 0)

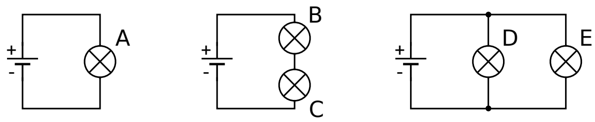
☐ Anzahl älterer (nicht jüngerer!) Schwestern (z.B. 2)

☐☐ 1. und 2. Buchstabe des Geburtsorts (z.B. HA für Hamburg)

☐☐ Letzte und vorletzte Ziffer des Geburtsjahres (z.B. 93 für 1993)

Aufgabe 1

Die folgenden drei Stromkreise bestehen aus identischen Glühlampen und identischen, idealen Batterien. (Nehmen Sie an, dass die Batterien ideale Spannungsquellen sind, d. h. ihr Innenwiderstand ist Null.)



Sortieren Sie die fünf Glühlampen A bis E entsprechend ihrer Helligkeit.
(Bitte verwenden Sie hierzu die Vergleichsoperatoren „>“, „<“ und „=“.)

Begründen Sie kurz.

Bitte beachten Sie die Rückseite!

Test in EE1ME, November 15th, 2016, version A, page 1, German original

Identification Code

1st and 2nd letter of your mother's first name (e.g. SA for Sandra)

Your day of birth (e.g. 07 for February 7th)

1st and 2nd letter of your father's first name (e.g. CH for Christian)

Number of older (not younger!) brothers (e.g. 0)

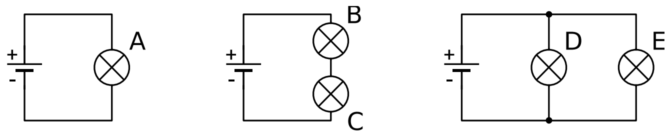
Number of older (not younger!) sisters (e.g. 2)

1st and 2nd letter of your place of birth (e.g. HA for Hamburg)

Second but last and last digit of your year of birth (e.g. 93 for 1993)

Task 1

The following three circuits contain identical bulbs and identical ideal batteries. (Assume that the batteries are ideal voltage sources, i.e. they have no internal resistance.)



Rank the 5 bulbs by their brightness.
(Please use the relational operators ‘>’, ‘<’, and ‘=’.)

Briefly explain your reasoning.

Please turn the page!

Test in EE1ME, November 15th, 2016, version A, page 1, English translation

Zuordnungscode

1. und 2. Buchstabe des Vornamens der Mutter (z.B. SA für Sandra)

Eigener Geburtstag (z.B. 07 für 7. Februar)

1. und 2. Buchstabe des Vornamens des Vaters (z.B. CH für Christian)

Anzahl älterer (nicht jüngerer!) Brüder (z.B. 0)

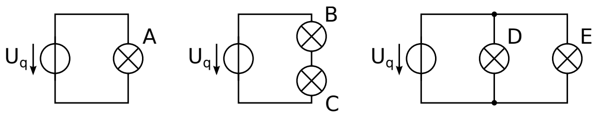
Anzahl älterer (nicht jüngerer!) Schwestern (z.B. 2)

1. und 2. Buchstabe des Geburtsorts (z.B. HA für Hamburg)

Letzte und vorletzte Ziffer des Geburtsjahres (z.B. 93 für 1993)

Aufgabe 1

Die folgenden drei Stromkreise bestehen aus identischen Glühlampen und identischen, idealen Spannungsquellen.



Sortieren Sie die fünf Glühlampen A bis E entsprechend ihrer Helligkeit.
(Bitte verwenden Sie hierzu die Vergleichsoperatoren „>“, „<“ und „=“.)

Begründen Sie kurz.

Bitte beachten Sie die Rückseite!

Test in EE1ME, November 15th, 2016, version B, page 1, German original

Identification Code

1st and 2nd letter of your mother's first name (e.g. SA for Sandra)

Your day of birth (e.g. 07 for February 7th)

1st and 2nd letter of your father's first name (e.g. CH for Christian)

Number of older (not younger!) brothers (e.g. 0)

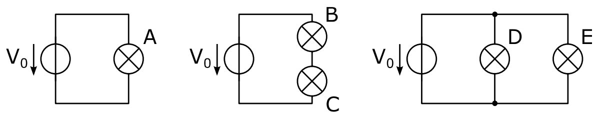
Number of older (not younger!) sisters (e.g. 2)

1st and 2nd letter of your place of birth (e.g. HA for Hamburg)

Second but last and last digit of your year of birth (e.g. 93 for 1993)

Task 1

The following three circuits contain identical bulbs and identical ideal voltage sources.



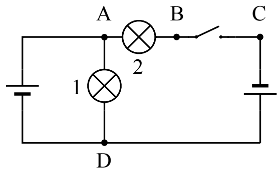
Rank the 5 bulbs by their brightness.
(Please use the relational operators '>', '<', and '='.)

Briefly explain your reasoning.

Please turn the page!

Aufgabe 2

Die Schaltung rechts enthält zwei identische Batterien, die als ideale Spannungsquellen betrachtet werden können. Der kurze Strich kennzeichnet den Minus-Pol der Batterie. Die Lampen 1 und 2 sind identisch, der Schalter ist geöffnet.



Bei offenem Schalter:

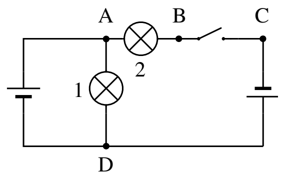
Sortieren Sie die Spannungen U_{AB}, U_{AC}, U_{AD} und U_{BC} nach ihrem Betrag. Sollten zwei Spannungen gleich groß oder eine Spannung gleich Null sein, geben Sie dies ausdrücklich an. Verwenden Sie die Vergleichsoperatoren >, < und =.

Begründen Sie kurz.

Vielen Dank!

Test in EE1ME, November 15th, 2016, versions A&B, page 2, German original

Task 2



The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The short line denotes the negative terminal of the battery. Bulbs 1 and 2 are identical, the switch is open.

With the switch in the open position:

Rank the voltages V_{AB}, V_{AC}, V_{AD}, and V_{BC} by their absolute value. If two voltages have the same absolute value or one voltage is zero, state this explicitly. Use the relational operators >, <, and =.

Briefly explain your reasoning.:

Thank you!

E.20 QUIZ IN EE1ME, DECEMBER 6TH, 2016

Zuordnungscode

☐☐ 1. und 2. Buchstabe des Vornamens der Mutter (z.B. SA für Sandra)

☐☐ Eigener Geburtstag (z.B. 07 für 7. Februar)

☐☐ 1. und 2. Buchstabe des Vornamens des Vaters (z.B. CH für Christian)

☐ Anzahl älterer (nicht jüngerer!) Brüder (z.B. 0)

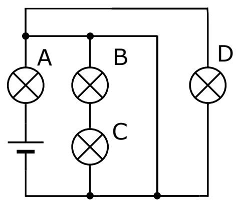
☐ Anzahl älterer (nicht jüngerer!) Schwestern (z.B. 2)

☐☐ 1. und 2. Buchstabe des Geburtsorts (z.B. HA für Hamburg)

☐☐ Letzte und vorletzte Ziffer des Geburtsjahres (z.B. 93 für 1993)

Aufgabe 1

Der rechts abgebildete Stromkreis besteht aus identischen Glühlampen und einer Batterie, die als ideale Spannungsquelle betrachtet werden kann.



a) Beschreiben Sie, wie die Schaltungselemente miteinander verbunden sind.

b) Sortieren Sie die Lampen nach ihrer Helligkeit. Sollten zwei Lampen gleich hell oder eine Lampe gar nicht leuchten, geben Sie dies ausdrücklich an. Verwenden Sie die Vergleichsoperatoren >, < und =.

Begründen Sie kurz.

Bitte beachten Sie auch die Rückseite!

Test in EE1ME, December 6th, 2016, page 1, German original

Identification Code

1st and 2nd letter of your mother's first name (e.g. SA for Sandra)

Your day of birth (e.g. 07 for February 7th)

1st and 2nd letter of your father's first name (e.g. CH for Christian)

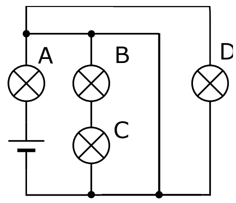
Number of older (not younger!) brothers (e.g. 0)

Number of older (not younger!) sisters (e.g. 2)

1st and 2nd letter of your place of birth (e.g. HA for Hamburg)

Second but last and last digit of your year of birth (e.g. 93 for 1993)

Task 1



The circuit at right contains identical bulbs and a battery which can be treated as an ideal voltage source.

a) Explain how the different circuit elements are connected with each other.

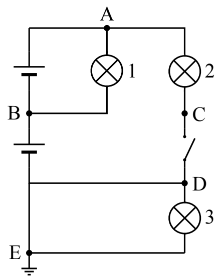
b) Rank the bulbs A, B, C, and D by their brightness. State explicitly, if two bulbs have the same brightness or one bulb does not glow at all. Use the relational operators >, <, and =.

Briefly explain your reasoning.

Please turn the page!

Test in EE1ME, December 6th, 2016, page 1, English translation

Aufgabe 2



Die Schaltung rechts enthält zwei identische Batterien, die als ideale Spannungsquellen betrachtet werden können. Der lange Strich kennzeichnet die positive Klemme der Batterie, der kurze Strich die negative Klemme. Die Glühlampen 1 bis 3 sind ebenfalls identisch, an Punkt E ist eine Erdung angeschlossen.

Der Schalter ist geöffnet.

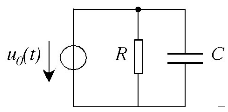
a. Ordnen Sie die Spannungen U_{AB}, U_{AC}, U_{AD} und U_{CD} nach ihrem Betrag. Verwenden Sie dafür die Vergleichsoperatoren >, < und =. Wenn zwei Spannungen gleich groß oder eine Spannung gleich Null ist, geben Sie dies ausdrücklich an.

Begründen Sie kurz.

b. Sortieren Sie die Punkte A bis E nach ihrem elektrischen Potential Φ_A bis Φ_E. Verwenden Sie dafür die Vergleichsoperatoren >, < und =. Wenn zwei Potentiale gleich groß oder ein Potentiale gleich Null ist, geben Sie dies ausdrücklich an.

Begründen Sie kurz.

Aufgabe 3



Die Schaltung rechts enthält eine ideale Wechselspannungsquelle $u_0(t)$ mit $u_0(t) = \hat{u}_0 \cos(\omega t + \varphi_0)$, sowie einen Widerstand R und eine Kapazität C. Die an den Bauteilen anliegenden Spannungen werden mit $u_R(t)$ und $u_C(t)$ bezeichnet; die entsprechenden Ströme mit $i_R(t)$ und $i_C(t)$. Der durch die Spannungsquelle fließende Strom werde mit $i_0(t)$ bezeichnet.

Zwei sinusförmige Signale haben die gleiche Phase, wenn sie ihre Maximalwerte (bei entsprechend gewähltem Vorzeichen) zu gleichen Zeitpunkten erreichen.

Tritt in den nachfolgenden Teilaufgaben zwischen den jeweils genannten Signalen eine Phasenverschiebung auf oder haben die beiden Signale die gleiche Phase?

Bitte *begründen* Sie jeweils stichwortartig Ihre Antwort.

a. $u_R(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

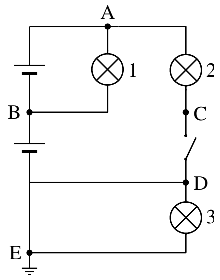
b. $u_C(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

c. $i_R(t)$ und $i_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

d. $i_0(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

Test in EE1ME, December 6th, 2016, page 2, German original

Task 2



The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery, the short line the negative terminal. Bulbs 1 to 3 are identical, node E is connected to ground.

The switch is in the open position.

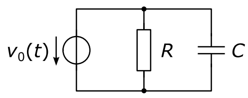
a. Rank the voltages V_{AB}, V_{AC}, V_{AD}, and V_{CD} by their absolute value. Use the relational operators >, <, and =. If two voltages have the same absolute value or one voltage is zero, state this explicitly.

Briefly explain your reasoning.

b. Rank nodes A to E by their electric potentials Φ_A to Φ_E. Use the relational operators >, <, and =. If two potentials have the same absolute value or one potential is zero, state this explicitly.

Briefly explain your reasoning.

Task 3



The circuit at right contains an ideal AC voltage source $v_0(t) = \hat{v}_0 \cos(\omega t + \varphi_0)$, a resistance R, and a capacitance C. The voltages over the components are denoted by $v_R(t)$ and $v_C(t)$; the corresponding currents are $i_R(t)$ and $i_C(t)$. The current through the source is denoted by $i_0(t)$.

Two sinusoidal signals are in phase if they reach their maxima (with the same sign) at the same time.

Is there a phase shift between the following signals or are they in phase?

Please *explain* your answers briefly.

a. $v_R(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
Explanation:

b. $v_C(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
Explanation:

c. $i_R(t)$ and $i_0(t)$ ☐ phase shift ☐ in phase
Explanation:

d. $i_0(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
Explanation:

E.21 QUIZ IN EE1UK, FEBRUARY 8TH, 2017

Identification Code

1st and 2nd letter of your mother’s first name (e.g. SA for Sandra)

Your day of birth (e.g. 07 for February 7th)

1st and 2nd letter of your father’s first name (e.g. CH for Christian)

Number of older (not younger!) brothers (e.g. 0)

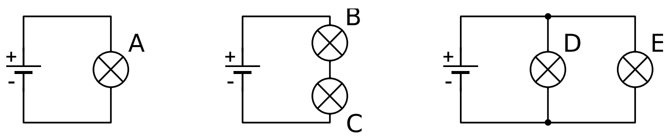
Number of older (not younger!) sisters (e.g. 2)

1st and 2nd letter of your place of birth (e.g. HA for Hamburg)

Second but last and last digit of your year of birth (e.g. 93 for 1993)

Task 1

The three circuits beneath contain identical bulbs and identical, ideal batteries. (Assume that the batteries are ideal voltage sources, i.e. they have no internal resistance.)



Rank the 5 bulbs according to their brightness.
(Use the relational operators ‘>‘, ‘<‘, and ‘=‘.)

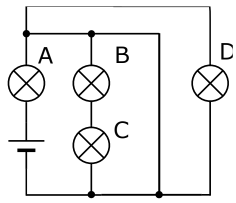
Briefly explain your reasoning.

Please turn the page!

Quiz in EE1UK, February 8th, 2017, page 1, English original

Task 2

The circuit at right contains identical bulbs and a battery which can be treated as an ideal voltage source.



a) Explain how the different circuit elements are connected with each other.

b) Rank bulbs A, B, C, and D according to their brightness. State explicitly, if two bulbs have the same brightness or one bulb does not glow at all. Use the relational operators >, <, and =.

Briefly explain your reasoning.

E.22 QUIZ IN EE1UK, FEBRUARY 31ST, 2017

Identification Code

1st and 2nd letter of your mother's first name (e.g. SA for Sandra)

Your day of birth (e.g. 07 for February 7th)

1st and 2nd letter of your father's first name (e.g. CH for Christian)

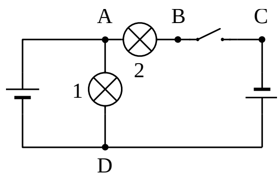
Number of older (not younger!) brothers (e.g. 0)

Number of older (not younger!) sisters (e.g. 2)

1st and 2nd letter of your place of birth (e.g. HA for Hamburg)

Second but last and last digit of your year of birth (e.g. 93 for 1993)

Task 1



The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The short line denotes the negative terminal of the battery. Bulbs 1 and 2 are identical, the switch is open.

With the switch in the open position:

Rank voltages V_{AB}, V_{AC}, V_{AD}, and V_{BC} by their absolute value. If two voltages have the same absolute value or one voltage is zero, state this explicitly. Use the relational operators >, <, and =.

Briefly explain your reasoning.

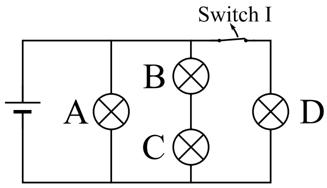
Thank you!

E.23 QUIZ IN EE1UK, MARCH 22ND, 2017

Student ID

Task 1

The circuit at right contains identical bulbs and an ideal battery. (Assume that the battery is an ideal voltage source, i.e. it has no internal resistance.)
The switch is closed at first.



Rank the 4 bulbs according to their brightness.
(Please use the relational operators ‘>‘, ‘<‘, and ‘=‘.)

Briefly explain your reasoning.

Now, the switch is opened.
By opening the switch, the brightness of bulb A ...

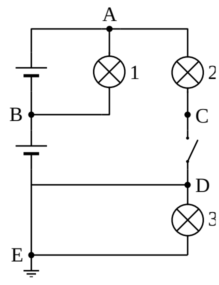
☐ *increases.*
☐ *stays the same.*
☐ *decreases.*

Briefly explain your Reasoning.

Please turn the page!

Quiz in EE1UK, March 22nd, 2017, page 1, English original

Task 2



The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery, the short line the negative terminal. All three bulbs are identical, node E is connected to ground.

The switch is in the open position.

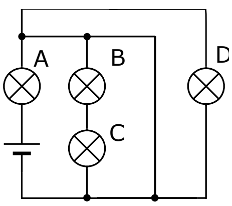
a. Rank voltages V_{AB}, V_{AC}, V_{AD}, and V_{CD} by their absolute value. Use the relational operators >, <, and =. If two voltages have the same absolute value or one voltage is zero, state this explicitly.

Explanation:

b. Rank nodes A through E by their electric potentials Φ_A to Φ_E. Use the relational operators >, <, and =. If two potentials have the same absolute value or one potential is zero, state this explicitly.

Explanation:

Task 3



The circuit at right contains identical bulbs and a battery which can be treated as an ideal voltage source.

a) Rank bulbs A, B, C, and D according to their brightness. State explicitly, if two bulbs have the same brightness or one bulb does not glow at all. Use the relational operators >, <, and =.

Briefly explain your reasoning.

E.24 QUIZ IN EE1ME, NOVEMBER 14TH, 2017

Zuordnungscode

☐☐ 1. und 2. Buchstabe des Vornamens der Mutter (z.B. SA für Sandra)

☐☐ Eigener Geburtstag (z.B. 07 für 7. Februar)

☐☐ 1. und 2. Buchstabe des Vornamens des Vaters (z.B. CH für Christian)

☐ Anzahl älterer (nicht jüngerer!) Brüder (z.B. 0)

☐ Anzahl älterer (nicht jüngerer!) Schwestern (z.B. 2)

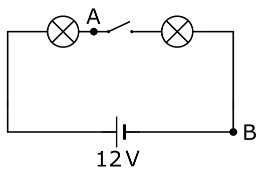
☐☐ 1. und 2. Buchstabe des Geburtsorts (z.B. HA für Hamburg)

☐☐ Letzte und vorletzte Ziffer des Geburtsjahres (z.B. 93 für 1993)

Aufgabe 1

Die folgende Schaltung enthält zwei identische Lampen, eine 12V Batterie und einen Schalter (offen).

Wie groß ist die Spannung zwischen den Punkten A und B?



- ☐ 0 V
- ☐ 3 V
- ☐ 6 V
- ☐ 12 V
- ☐ keine der obigen Antworten

Bitte geben Sie eine <u>detaillierte</u> Begründung!

Bitte beachten Sie die Rückseite!

Test in EE1ME, November 14th, 2017, page 1, German original

Identification Code

1st and 2nd letter of your mother's first name (e.g. SA for Sandra)

Your day of birth (e.g. 07 for February 7th)

1st and 2nd letter of your father's first name (e.g. CH for Christian)

Number of older (not younger!) brothers (e.g. 0)

Number of older (not younger!) sisters (e.g. 2)

1st and 2nd letter of your place of birth (e.g. HA for Hamburg)

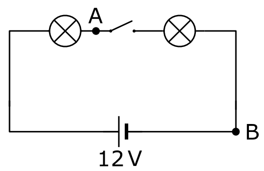
Second but last and last digit of your year of birth (e.g. 93 for 1993)

Task 1

The circuit below contains two identical bulbs, a 12V battery, and a switch (open).

What is the voltage between points A and B?

- ☐ 0 V
- ☐ 3 V
- ☐ 6 V
- ☐ 12 V
- ☐ none of the above



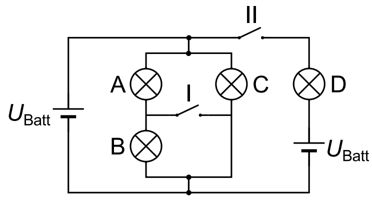
Please give a detailed explanation!

Please turn the page!

Test in EE1ME, November 14th, 2017, page 1, English translation

Aufgabe 2

Die Schaltung rechts enthält zwei identische Batterien, die als ideale Spannungsquellen mit der Spannung U_{Batt} betrachtet werden können. Der kurze Strich kennzeichnet den Minus-Pol der Batterie. Die vier Lampen sind ebenfalls identisch. Zunächst sind beide Schalter geöffnet.



a) Die Spannung an Schalter I ist
☐ gleich 0V. ☐ zwischen 0V und U_{Batt}. ☐ gleich U_{Batt}. ☐ größer als U_{Batt}.

Bitte begründen Sie Ihre Antwort!

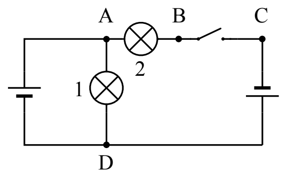
Nun wird Schalter I geschlossen, Schalter II bleibt geöffnet.

b) Durch schließen des Schalters I
☐ wird Lampe A heller. ☐ bleibt Lampe A gleich hell. ☐ wird Lampe A dunkler.

c) Durch schließen des Schalters I
☐ wird Lampe C heller. ☐ bleibt Lampe C gleich hell. ☐ wird Lampe C dunkler.

Aufgabe 3

Die Schaltung rechts enthält zwei identische Batterien, die als ideale Spannungsquellen betrachtet werden können. Der kurze Strich kennzeichnet den Minus-Pol der Batterie. Die Lampen 1 und 2 sind identisch, der Schalter ist geöffnet.
Bei offenem Schalter:



a) Sortieren Sie die Spannungen U_{AB}, U_{AC}, U_{AD} und U_{BC} nach ihrem Betrag. Sollten zwei Spannungen gleich groß sein, geben Sie dies ausdrücklich an.
Verwenden Sie die Vergleichsoperatoren >, < und =.

b) Geben Sie an ob folgende Spannungen gleich oder ungleich Null sind:

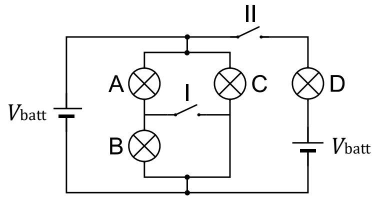
i)	U_{AB}:	☐ gleich 0 V	☐ ungleich 0 V
ii)	U_{AC}:	☐ gleich 0 V	☐ ungleich 0 V
iii)	U_{AD}:	☐ gleich 0 V	☐ ungleich 0 V
iv)	U_{BC}:	☐ gleich 0 V	☐ ungleich 0 V

Vielen Dank!

Test in EE1ME, November 14th, 2017, page 2, German original

Task 2

The circuit at right contains two identical batteries, which can be treated as ideal voltage sources with the voltage V_{batt}. The short line indicates the negative pole of the battery. The four bulbs are identical. At first, both switches are open.



a) The voltage across Switch I is
☐ equal to 0V. ☐ between 0V and V_{batt}. ☐ equal to V_{batt}. ☐ larger than V_{batt}.

Please explain your reasoning!

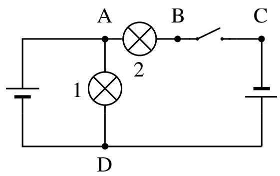
Now Switch I is closed, Switch II stays open.

b) By closing Switch I,
☐ Bulb A gets brighter. ☐ Bulb A remains equally bright. ☐ Bulb A gets darker.

c) By closing Switch I,
☐ Bulb C gets brighter. ☐ Bulb C remains equally bright. ☐ Bulb C gets darker.

Task 3

The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The short line denotes the negative terminal of the battery. Bulbs 1 and 2 are identical, the switch is open.
With the switch in the open position:



a) Rank the voltages V_{AB}, V_{AC}, V_{AD}, and V_{BC} by their absolute value. If two voltages have the same absolute value or one voltage is zero, state this explicitly. Use the relational operators >, <, and =.

b) Specify if the following voltages are equal or not equal to zero:

i)	V_{AB} :	☐ equal to 0 V	☐ not equal to 0 V
ii)	V_{AC} :	☐ equal to 0 V	☐ not equal to 0 V
iii)	V_{AD} :	☐ equal to 0 V	☐ not equal to 0 V
iv)	V_{BC} :	☐ equal to 0 V	☐ not equal to 0 V

Thank you!

Test in EE1ME, November 14th, 2017, page 2, English translation

E.25 QUIZ IN EE1ME, DECEMBER 5TH, 2017

Zuordnungscode

☐☐ 1. und 2. Buchstabe des Vornamens der Mutter (z.B. SA für Sandra)

☐☐ Eigener Geburtstag (z.B. 07 für 7. Februar)

☐☐ 1. und 2. Buchstabe des Vornamens des Vaters (z.B. CH für Christian)

☐ Anzahl älterer (nicht jüngerer!) Brüder (z.B. 0)

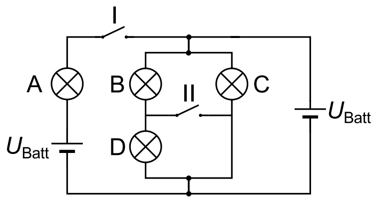
☐ Anzahl älterer (nicht jüngerer!) Schwestern (z.B. 2)

☐☐ 1. und 2. Buchstabe des Geburtsorts (z.B. HA für Hamburg)

☐☐ Letzte und vorletzte Ziffer des Geburtsjahres (z.B. 93 für 1993)

Aufgabe 1

Die Schaltung rechts enthält zwei identische Batterien, die als ideale Spannungsquellen mit der Spannung U_{Batt} betrachtet werden können. Der kurze Strich kennzeichnet den Minus-Pol der Batterie. Die vier Lampen sind ebenfalls identisch. Zunächst sind beide Schalter geöffnet.



a) Die Spannung an Schalter I ist
☐ gleich 0V. ☐ zwischen 0V und U_{Batt}. ☐ gleich U_{Batt}. ☐ größer als U_{Batt}.

Bitte begründen Sie Ihre Antwort!

b) Die Spannung an Schalter II ist
☐ gleich 0V. ☐ zwischen 0V und U_{Batt}. ☐ gleich U_{Batt}. ☐ größer als U_{Batt}.

Bitte begründen Sie Ihre Antwort!

Nun wird Schalter II geschlossen, Schalter I bleibt geöffnet.

c) Durch schließen des Schalters II
☐ wird Lampe B heller. ☐ bleibt Lampe B gleich hell. ☐ wird Lampe B dunkler.

d) Durch schließen des Schalters II
☐ wird Lampe C heller. ☐ bleibt Lampe C gleich hell. ☐ wird Lampe C dunkler.

Bitte beachten Sie die Rückseite!

Test in EE1ME, December 5th, 2017, page 1, German original

Identification Code

☐☐ 1st and 2nd letter of your mother's first name (e.g. SA for Sandra)

☐☐ Your day of birth (e.g. 07 for February 7th)

☐☐ 1st and 2nd letter of your father's first name (e.g. CH for Christian)

☐ Number of older (not younger!) brothers (e.g. 0)

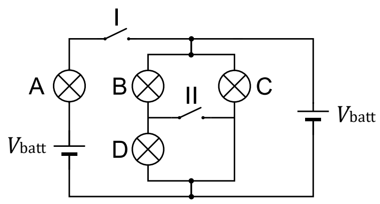
☐ Number of older (not younger!) sisters (e.g. 2)

☐☐ 1st and 2nd letter of your place of birth (e.g. HA for Hamburg)

☐☐ Second but last and last digit of your year of birth (e.g. 93 for 1993)

Task 1

The circuit at right contains two identical batteries, which can be treated as ideal voltage sources with the voltage V_{batt}. The short line indicates the negative pole of the battery. The four bulbs are also identical. At first, both switches are open.



a) The voltage across Switch I is
☐ equal to 0V. ☐ between 0V and V_{batt}. ☐ equal to V_{batt}. ☐ larger than V_{batt}.

Please explain your reasoning!

b) The voltage across Switch II is
☐ equal to 0V. ☐ between 0V and V_{batt}. ☐ equal to V_{batt}. ☐ larger than V_{batt}.

Please explain your reasoning!

Now Switch II is closed, Switch I stays open.

c) By closing Switch II,
☐ Bulb B gets brighter. ☐ Bulb B remains equally bright. ☐ Bulb B gets darker.

d) By closing Switch II,
☐ Bulb C gets brighter. ☐ Bulb C remains equally bright. ☐ Bulb C gets darker.

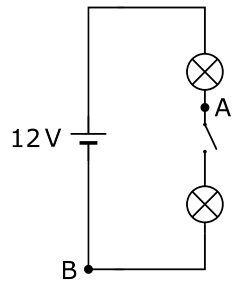
Please turn the page!

Test in EE1ME, December 5th, 2017, page 1, English translation

Aufgabe 2

Die folgende Schaltung enthält zwei identische Lampen, eine 12V Batterie und einen Schalter (offen).

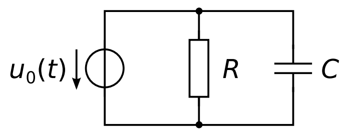
Wie groß ist die Spannung zwischen den Punkten A und B?



- ☐ 0 V
- ☐ 3 V
- ☐ 6 V
- ☐ 12 V
- ☐ keine der obigen Antworten

Aufgabe 3

Die Schaltung rechts enthält eine ideale Wechselspannungsquelle $u_0(t)$ mit $u_0(t) = \hat{u}_0 \cos(\omega t + \varphi_0)$, sowie einen Widerstand R und eine Kapazität C. Die an den Bauteilen anliegenden Spannungen werden mit $u_R(t)$ und $u_C(t)$ bezeichnet; die entsprechenden Ströme mit $i_R(t)$ und $i_C(t)$. Der durch die Spannungsquelle fließende Strom werde mit $i_0(t)$ bezeichnet.



Zwei sinusförmige Signale haben die gleiche Phase, wenn sie ihre Maximalwerte (bei entsprechend gewähltem Vorzeichen) zu gleichen Zeitpunkten erreichen.

Tritt in den nachfolgenden Teilaufgaben zwischen den jeweils genannten Signalen eine Phasenverschiebung auf oder haben die beiden Signale die gleiche Phase?

Bitte *begründen* Sie jeweils stichwortartig Ihre Antwort.

a. $u_R(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase

Begründung:

b. $u_C(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase

Begründung:

c. $i_R(t)$ und $i_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase

Begründung:

d. $i_0(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase

Begründung:

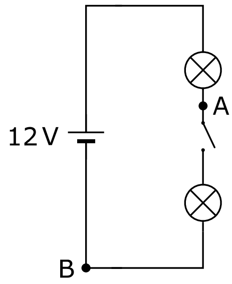
Test in EE1ME, December 5th, 2017, page 2, German original

Task 2

The circuit below contains two identical bulbs, a 12V battery and a switch (open).

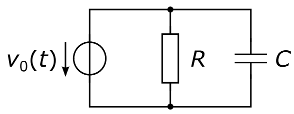
What is the voltage between points A and B?

- ☐ 0 V
- ☐ 3 V
- ☐ 6 V
- ☐ 12 V
- ☐ none of the above



Task 3

The circuit at right contains an ideal AC voltage source $v_0(t) = \hat{v}_0 \cos(\omega t + \varphi_0)$, a resistance R, and a capacitance C. The voltages over the components are denoted by $v_R(t)$ and $v_C(t)$; the corresponding currents are $i_R(t)$ and $i_C(t)$. The current through the source is denoted by $i_0(t)$.



Two sinusoidal signals are in phase if they reach their maxima (with the same sign) at the same time.

Is there a phase shift between the following signals or are they in phase?

Please *explain* your answers briefly.

a. $v_R(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase

Explanation:

b. $v_C(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase

Explanation:

c. $i_R(t)$ and $i_0(t)$ ☐ phase shift ☐ in phase

Explanation:

d. $i_0(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase

Explanation:

E.26 QUIZ IN EE1ME, NOVEMBER 20TH, 2018

Zuordnungscode

☐☐ 1. und 2. Buchstabe des Vornamens der Mutter (z.B. SA für Sandra)

☐☐ Eigener Geburtstag (z.B. 07 für 7. Februar)

☐☐ 1. und 2. Buchstabe des Vornamens des Vaters (z.B. CH für Christian)

☐ Anzahl älterer (nicht jüngerer!) Brüder (z.B. 0)

☐ Anzahl älterer (nicht jüngerer!) Schwestern (z.B. 2)

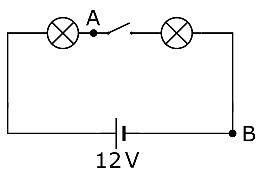
☐☐ 1. und 2. Buchstabe des Geburtsorts (z.B. HA für Hamburg)

☐☐ Letzte und vorletzte Ziffer des Geburtsjahres (z.B. 93 für 1993)

Aufgabe 1

Die folgende Schaltung enthält zwei identische Lampen, eine 12V Batterie und einen Schalter (offen).

Wie groß ist die Spannung zwischen den Punkten A und B?



- ☐ 0 V
- ☐ 3 V
- ☐ 6 V
- ☐ 12 V
- ☐ keine der obigen Antworten

Bitte beachten Sie die Rückseite!

Test in EE1ME, November 20th, 2018, page 1, German original

Identification Code

1st and 2nd letter of your mother's first name (e.g. SA for Sandra)

Your day of birth (e.g. 07 for February 7th)

1st and 2nd letter of your father's first name (e.g. CH for Christian)

Number of older (not younger!) brothers (e.g. 0)

Number of older (not younger!) sisters (e.g. 2)

1st and 2nd letter of your place of birth (e.g. HA for Hamburg)

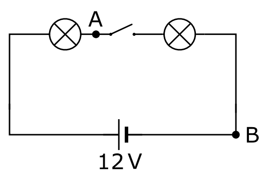
Second but last and last digit of your year of birth (e.g. 93 for 1993)

Task 1

The circuit below contains two identical bulbs, a 12V, battery and a switch (open).

What is the voltage between points A and B?

- ☐ 0 V
- ☐ 3 V
- ☐ 6 V
- ☐ 12 V
- ☐ none of the above

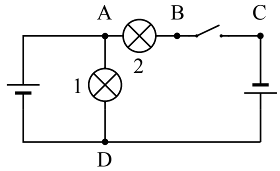


Please turn the page!

Test in EE1ME, November 20th, 2018, page 1, English translation

Aufgabe 2

Die Schaltung rechts enthält zwei identische Batterien, die als ideale Spannungsquellen betrachtet werden können. Der kurze Strich kennzeichnet den Minus-Pol der Batterie. Die Lampen 1 und 2 sind identisch, der Schalter ist geöffnet.



Bei offenem Schalter:

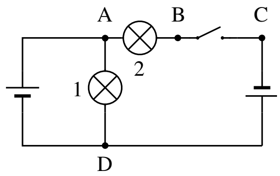
Sortieren Sie die Spannungen U_{AB}, U_{AC}, U_{AD} und U_{BC} nach ihrem Betrag. Sollten zwei Spannungen gleich groß oder eine Spannung gleich Null sein, geben Sie dies ausdrücklich an. Verwenden Sie die Vergleichsoperatoren >, < und =.

Begründen Sie kurz.

Vielen Dank!

Test in EE1ME, November 20th, 2018, page 2, German original

Task 2



The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The short line denotes the negative terminal of the battery. Bulbs 1 and 2 are identical, the switch is open.

With the switch in the open position:

Rank the voltages V_{AB}, V_{AC}, V_{AD}, and V_{BC} by their absolute value. If two voltages have the same absolute value or one voltage is zero, state this explicitly. Use the relational operators >, <, and =.

Briefly explain your reasoning.:

Thank you!

E.27 QUIZ IN EE1ME, DECEMBER 4TH, 2018

Zuordnungscode

☐☐ 1. und 2. Buchstabe des Vornamens der Mutter (z.B. SA für Sandra)

☐☐ Eigener Geburtstag (z.B. 07 für 7. Februar)

☐☐ 1. und 2. Buchstabe des Vornamens des Vaters (z.B. CH für Christian)

☐ Anzahl älterer (nicht jüngerer!) Brüder (z.B. 0)

☐ Anzahl älterer (nicht jüngerer!) Schwestern (z.B. 2)

☐☐ 1. und 2. Buchstabe des Geburtsorts (z.B. HA für Hamburg)

☐☐ Letzte und vorletzte Ziffer des Geburtsjahres (z.B. 93 für 1993)

Aufgabe 1

a) Ist die Spannung über einem offenen Schalter *immer* 0 V?

☐ Ja
☐ Nein
☐ Ich bin unsicher

Begründen Sie.

b) Ist die Spannung über einem geschlossenen Schalter *immer* 0 V?

☐ Ja
☐ Nein
☐ Ich bin unsicher

Begründen Sie.

Bitte beachten Sie auch die Rückseite!

Test in EE1ME, December 4th, 2018, page 1, German original

Identification Code

☐☐ 1st and 2nd letter of your mother's first name (e.g. SA for Sandra)

☐☐ Your day of birth (e.g. 07 for February 7th)

☐☐ 1st and 2nd letter of your father's first name (e.g. CH for Christian)

☐ Number of older (not younger!) brothers (e.g. 0)

☐ Number of older (not younger!) sisters (e.g. 2)

☐☐ 1st and 2nd letter of your place of birth (e.g. HA for Hamburg)

☐☐ Second but last and last digit of your year of birth (e.g. 93 for 1993)

Task 1

a) Is the voltage across an open switch *always* 0V?

- ☐ Yes
- ☐ No
- ☐ I am unsure

Please explain your reasoning.

b) Is the voltage across a closed switch *always* 0V?

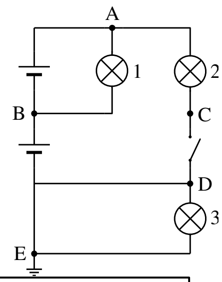
- ☐ Yes
- ☐ No
- ☐ I am unsure

Please explain your reasoning.

Please turn the page!

Test in EE1ME, December 4th, 2018, page 1, English translation

Aufgabe 2



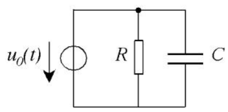
Die Schaltung rechts enthält zwei identische Batterien, die als ideale Spannungsquellen betrachtet werden können. Der lange Strich kennzeichnet die positive Klemme der Batterie, der kurze Strich die negative Klemme. Die Glühlampen 1 bis 3 sind ebenfalls identisch, an Punkt E ist eine Erdung angeschlossen.

Der Schalter ist geöffnet.

Ordnen Sie die Spannungen U_{AB}, U_{AC}, U_{AD} und U_{CD} nach ihrem Betrag. Verwenden Sie dafür die Vergleichsoperatoren >, < und =. Wenn zwei Spannungen gleich groß oder eine Spannung gleich Null ist, geben Sie dies ausdrücklich an.

Begründen Sie kurz.

Aufgabe 3



Die Schaltung rechts enthält eine ideale Wechselspannungsquelle $u_0(t)$ mit $u_0(t) = \hat{u}_0 \cos(\;\; t + \;\;_0)$, sowie einen Widerstand R und eine Kapazität C. Die an den Bauteilen anliegenden Spannungen werden mit $u_R(t)$ und $u_C(t)$ bezeichnet; die entsprechenden Ströme mit $i_R(t)$ und $i_C(t)$. Der durch die Spannungsquelle fließende Strom werde mit $i_0(t)$ bezeichnet.

Zwei sinusförmige Signale haben die gleiche Phase, wenn sie ihre Maximalwerte (bei entsprechend gewähltem Vorzeichen) zu gleichen Zeitpunkten erreichen.

Tritt in den nachfolgenden Teilaufgaben zwischen den jeweils genannten Signalen eine Phasenverschiebung auf oder haben die beiden Signale die gleiche Phase?

Bitte *begründen* Sie jeweils stichwortartig Ihre Antwort.

a. $u_R(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

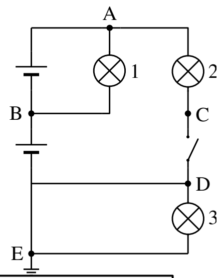
b. $u_C(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

c. $i_R(t)$ und $i_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

d. $i_0(t)$ und $u_0(t)$ ☐ Phasenverschiebung ☐ gleiche Phase
Begründung:

Test in EE1ME, December 4th, 2018, page 2, German original

Task 2



The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The long line indicates the positive terminal of the battery, the short line the negative terminal. Bulbs 1 to 3 are identical, node E is connected to ground.

The switch is in the open position.

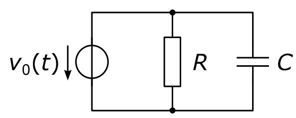
a. Rank the voltages V_{AB}, V_{AC}, V_{AD}, and V_{CD} by their absolute value. Use the relational operators >, <, and =. If two voltages have the same absolute value or one voltage is zero, state this explicitly.

Briefly explain your reasoning.

b. Rank nodes A to E by their electric potentials Φ_A to Φ_E. Use the relational operators >, <, and =. If two potentials have the same absolute value or one potential is zero, state this explicitly.

Briefly explain your reasoning.

Task 3



The circuit at right contains an ideal AC voltage source $v_0(t) = \hat{v}_0 \cos(\omega t+\varphi_0)$, a resistance R, and a capacitance C. The voltages over the components are denoted by $v_R(t)$ and $v_C(t)$; the corresponding currents are $i_R(t)$ and $i_C(t)$. The current through the source is denoted by $i_0(t)$.

Two sinusoidal signals are in phase if they reach their maxima (with the same sign) at the same time.

Is there a phase shift between the following signals or are they in phase?

Please *explain* your answers briefly.

a. $v_R(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
Explanation:

b. $v_C(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
Explanation:

c. $i_R(t)$ and $i_0(t)$ ☐ phase shift ☐ in phase
Explanation:

d. $i_0(t)$ and $v_0(t)$ ☐ phase shift ☐ in phase
Explanation:

E.28 QUIZ IN EE1ME, NOVEMBER 12TH, 2019

This test was identical to the one shown in Appendix E.26.

E.29 QUIZ IN EE1ME, NOVEMBER 26TH, 2019

This test was identical to the one shown in Appendix E.27.

F

INTERVIEWS ON ELECTRIC CIRCUITS AND THEIR REPRESENTATIONS

This appendix describes exploratory student interviews conducted in early 2014. This kind of interview was introduced as a research method in Chapter 5. Observations made in the interviews were referenced in Chapters 7 and 8.

F.1 CONTEXT OF THE INVESTIGATION

The courses EE1ME and EE1EE are described in Section 4.2 (p. 53).

In early 2014, an announcement was made in a lecture of the courses EE1ME and EE1EE, asking for voluntary participants in subject-matter interviews. Possible time-slots for the interviews were announced and students who were willing to participate were asked to indicate their availability. In the announcement, students were told that the interview lasted approximately 60 minutes. They were not offered any financial incentive to participate, but it was advertised that their participation would not only help the research of the Engineering Education Research Group (EERG) at Hamburg University of Technology[1] (TUHH), but also help to improve teaching for future generations of students. Students were informed that the subject of the interviews would be their understanding of electrical engineering, but were not told any specifics.

The interviews took place at the end of the winter term 2013/14, after all relevant instruction, but before the exams in the respective courses (see Appendix A). At the time of the interviews some students had already started to prepare for the exams, some had not.

Initially, 11 students offered to participate. With 10 of these, it was possible to schedule an interview in the intended time frame. 9 of the 10 interviewees could be considered average students, neither particularly strong nor particularly weak. One interviewee, however, had trouble to understand the questions they were asked. Their difficulty might have been amplified by a language barrier. This student's interview was not used in this thesis.

F.2 INTERVIEW SETTING

Most interviews were conducted by two interviewers. They sat at either side of a large table. The student was seated at the end of the table. This seating arrangement made it possible to engage in a

1 "Technische Universität Hamburg" in German, formerly "Technische Universität Hamburg-Harburg".

discussion of subject matter while still preventing the student from reading the notes the interviewer might take.

The interviews were conducted in German as semi-structured, individual demonstration interviews. In addition to pieces of paper explaining the individual tasks, each interviewee was given a piece of paper to write on. A video camera was used to record the audio of the interview as well as a video image of the paper in front of the student. To provide as much anonymity as possible, the camera was framed so that only the piece of paper as well as the interviewee's hand and arm could be seen in the video. Participants' consent for the video recording was recorded on camera. Students' written notes were later scanned. Using the video, it was possible to reconstruct at which point in time specific parts were written.

The interviews were recorded, transcribed, and evaluated in German. Only parts quoted in this thesis and other publications were translated.

F.3 INTERVIEW PROCESS

At the start of the interview, students were instructed about the interview process. They were warned that the interviewers would not comment wether or not an answer was correct, but might drill down on specific statements, not to embarrass the interviewee, but to truly understand their beliefs. The interviewers then introduced themselves and asked the interviewee to briefly describe their educational history and experience with electrical engineering. After that, the interview itself started. The mode of questioning is further explained in Section 5.4.2.

F.4 INTERVIEW QUESTIONS

Each interview consisted of three independent questions that were used in a fixed order.

F.4.1 *Task 0*

The first task of the interview was labeled "Task 0", as it partially functioned as a warm-up question. The task was introduced to students as a precursor.

Students were given the sheet of paper shown in Figure F.1 and asked to determine if the systems of equations were solvable. The four possible answering options were shown at the bottom of the sheet.

Students were not instructed what was meant by "solvable" and not coached in how to proceed. A mathematics course that addresses the solvability of systems of linear equations was mandatory in the same or an earlier semester than the electrical engineering course the par-

System A

$$\begin{array}{rrrrl} \text{(I)} & x & +2y & & =15 \\ \text{(II)} & 2x & & -z & =2 \\ \text{(III)} & x & -y & +2z & =5 \\ \text{(IV)} & 2x & & -z & =12 \end{array}$$

System B

$$\begin{array}{rrrrl} \text{(I)} & & +y & +2z & =14 \\ \text{(II)} & -x & +2y & & =9 \\ \text{(III)} & 2x & +y & -z & =8 \\ \text{(IV)} & -x & +2y & & =9 \end{array}$$

- ☐ System A is solvable, System B is **not** solvable
- ☐ System A is **not** solvable, System B is solvable
- ☐ **Both** Systems are solvable
- ☐ **Neither** System is solvable.

Figure F.1: Task 0 in the interviews.

ticipants attended. As with the other tasks, students were asked and if necessary reminded to think aloud.

This task was included to test students' ability to identify conflicting equations in a system of linear equations (equations II and IV in System A in Figure F.1 conflict with each other). This ability was then compared with their ability to identify illegal circuit configurations, such as parallel voltage sources with different source voltages that could occur in Task 1. While the research on that topic is not addressed in this thesis, it was discussed in a publication (Timmermann and Kautz, 2013).

F.4.2 *Task 1*

The second task in the interview was also the first task on electrical engineering. It focused on the circuit shown in Figure F.2a. This task was designed to analyze students' ability to recognize illegal circuit layouts.
The task was split into eight questions that were always addressed in the same order:

1.1.a If the source current I_A of the current source was changed, but the source voltage V_B of the voltage source stayed the same, would the current I_3 through resistor R_3 change?

1.1.b If the source current I_A of the current source was changed, but the source voltage V_B of the voltage source stayed the same, would the voltage V_3 across resistor R_3 change?

1.2.a Is it possible to insert a voltage source between points X and Y, as e. g. V_C in Figure F.2b, so that the currents I_1, I_2, and I_3, i. e. the currents through resistors R_1, R_2, and R_3 do not change? If so, what values are allowed/required for the source voltage of that new voltage source?

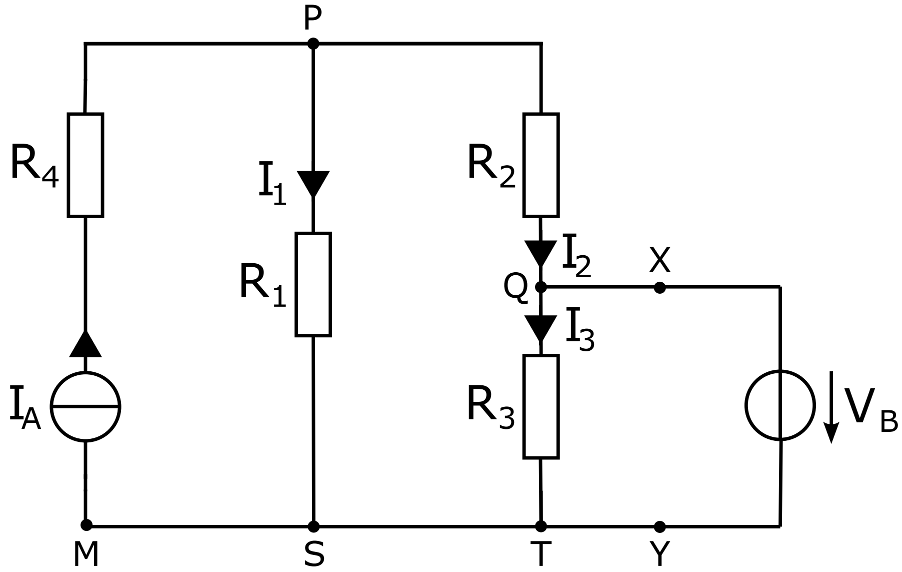
1.2.b Is it possible to insert a voltage source between points X and Y, as e. g. V_C in Figure F.2b, if the the currents I_1, I_2, and I_3, i. e. the currents through resistors R_1, R_2, and R_3 are allowed change? If so, what values are allowed/required for the source voltage of that new voltage source?

2.1.a If the source voltage V_B of the voltage source was changed, but the source current I_A of the current source stayed the same, would the voltage V_4 across resistor R_4 change?

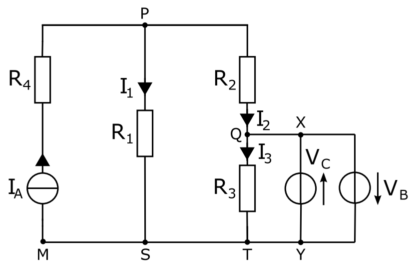
2.1.b If the source voltage V_B of the voltage source was changed, but the source current I_A of the current source stayed the same, would the current I_4 through resistor R_4 change?

2.2.a Is it possible to insert a current source between points S and M, as e. g. I_D in Figure F.2c, so that the currents I_1, I_2, and I_3, i. e. the currents through resistors R_1, R_2, and R_3 do not change? If so, what values are allowed/required for the source current of that new current source?

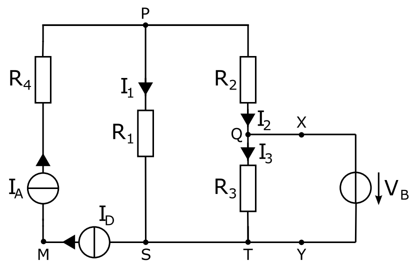
2.2.b Is it possible to insert a current source between points X and Y, as e. g. I_D in Figure F.2c, if the currents I_1, I_2, and I_3, i. e. the currents through resistors R_1, R_2, and R_3 are allowed change? If so, what values are allowed/required for the source current of that new current source?



(a) The base circuit used for Task 1.



(b) Base circuit with a second voltage (V_C) source in parallel.



(c) Base circuit with a second current source (I_D) in series.

Figure F.2: Circuit variants used in task 1 in the interviews.

F.4.3 *Task 2*

The second task varied, depending on the course the student was in. Students in the course EE1ME were presented with some real-world circuits and asked to explain them and draw equivalent circuit diagrams. Students in the course EE1EE were presented with questions on their understanding of electric fields and the electric potential of these fields. While neither of these questions is relevant for this research project, some were discussed in a prior publication (Timmermann and Kautz, 2013).

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LIST OF ACRONYMS

AC alternating current

APOS Action, Process, Object, Schema
The name APOS-Theory is based on this acronym of its key elements.

DBER discipline-based educational research

DC direct current

DIRECT direct current resistive electrical circuits test
A concept inventory developed by Engelhardt (1997).

DtD Decoding the Disciplines

EER engineering education research

EERG Engineering Education Research Group

FCI Force Concept Inventory
A concept inventory developed by Hestenes et al. (1992).

IEC International Electrotechnical Commission

IEV International Electrotechnical Vocabulary

IOaI Intended Observations and Inferences
Type of document described in Section 8.1.

KCL Kirchhoff's Current Law

KVL Kirchhoff's Voltage Law

PEG Physics Education Group

PER physics education research

RC resistor and capacitor

SGIC self-generated identification code
See Section 6.1.

SoTL Scholarship of Teaching and Learning

STEM science, technology, engineering, and mathematics

TA teaching assistant

TUHH Hamburg University of Technology[1]

UK United Kingdom

USA United States of America

1 "Technische Universität Hamburg" in German, formerly "Technische Universität Hamburg-Harburg".

About the Author

Dion Timmermann is an electrical engineer and educational researcher.

The systematic inquiry of students' conceptual understanding has enabled educators to move away from the assumption that students simply make random mistakes towards the realization that many incorrect answers given by students are based on internally consistent, albeit flawed, mental models. Helping students to overcome these flawed mental models often requires instruction that specifically addresses common misconceptions and uses active learning methods. Tutorial worksheets are research-based learning materials that support such instruction. They have been developed by several research groups world-wide. Most of the development and evaluation was focused on different physics courses and their curriculum.

This thesis provides a comprehensive overview of engineering students' understanding of basic electric circuit concepts, focusing on current and voltage in the context of simple circuits such as parallel and series connections as well as open and short circuits. It is found that the common misconceptions about electric circuit concepts that had previously been identified with students in physics courses also occur in engineering courses, albeit less frequently. The frequency of these misconceptions is shown to be reduced by the Tutorials Current and Resistance and Voltage. Using an approach that is informed by the Decoding the Disciplines framework as well as APOS-Theory, these Tutorials are analyzed and further refined.

Additional student difficulties and misconceptions that are related to concepts primarily taught in engineering courses are identified in this thesis. Most prominently, the voltage across an open switch is found to be a critical test for students' understanding of Kirchhoff's Voltage Law. Of more than 5500 students, 52% believed the voltage across an open switch to be always zero. A Tutorial that uses the electric potential to address this misconception is documented and evaluated, showing that the electric potential can be an effective tool in helping students overcome their misconceptions about voltage.

Using threshold concept theory, the importance of the concept of the electric potential is underlined, adding another argument why it should be considered a corner stone of instruction on DC circuits.

This thesis is the first German dissertation on university-level electrical engineering education research. To characterize its relation to international discipline-based educational research as well as educational research in Germany, the thesis contains an extensive introduction to the theoretical frameworks, methods, and methodology that inform it and the work of the Engineering Education Research Group at Hamburg University of Technology.

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