Using Potential to Help Students Understand Voltage: First Steps in Implementing Effective Instruction

D. Timmermann[1]
Research Assistant, Engineering Education Research Group
Hamburg University of Technology
Hamburg, Germany
E-Mail: dion.timmermann@tuhh.de

F. Lehmann
Research Assistant, Engineering Education Research Group
Hamburg University of Technology
Hamburg, Germany
E-Mail: felix.lehmann@tuhh.de

C. Kautz
Professor for Engineering Education, Engineering Education Research Group
Hamburg University of Technology
Hamburg, Germany
E-Mail: kautz@tuhh.de

Keywords: student understanding; tutorial worksheet

INTRODUCTION

Together with current and resistance, voltage is one of the most fundamental concepts in electrical engineering. Understanding it and its properties, as e. g. formulated by Kirchhoff's Voltage Law (KVL), is a key factor for success in circuit analysis.

In an earlier publication, we presented efforts to help students gain a better understanding of the concept of voltage. To achieve this, we designed a four-page tutorial-worksheet about the electric potential. We hoped that through its close relation to voltage, an understanding of potential would also further students' understanding of voltage. As described in that publication, we administered a post-test whose results were catastrophic. It showed that virtually no student had a functional understanding of potential and voltage across an open switch in a test that most instructors would judge fair. [1]

Despite this setback, we are still confident that an understanding of potential can help students with voltage and KVL, and that tutorial worksheets are a good approach to teach this subject matter. Because of this, we produced an updated version of the

[1] Corresponding Author
D. Timmermann
dion.timmermann@tuhh.de

worksheet which was then was used in the same introductory electrical engineering course. This paper presents the updated worksheet and its evaluation using a pre- and post-test.

The worksheets designed by our group are modeled after the “Tutorials in Introductory Physics” created by the Physics Education Group at the University of Washington. [2] They are designed to be worked on collaboratively by groups of about four students, who answer and discuss conceptual questions. These questions are designed to confront students with common misconceptions. Based on our own research, we have developed many tutorial worksheets and gained considerable experience in their usage in class. [3]

In this paper, we first give an overview of our methodology and the course this study was conducted on. Then, we will present parts of the tutorial worksheet and motivate our decisions made during its design. We will also describe the pre- and post-test used to evaluate the tutorial and show students’ answers. These allow us to draw conclusions and suggest future improvements to the material developed.

1 METHODOLOGY

Our research is based on the assumption (supported by prior observation) that students have or develop alternative ideas about key concepts in subject matter [4]. One goal of instruction is then to help students overcome these alternative ideas through a process of conceptual change [5]. To achieve this change, suitable instructional material, as e. g. tutorial worksheets, can be beneficial [4]. This leads us to use empirical methods for gathering student statements in verbal, short-answer, or multiple-choice form that allow us to make inferences about their understanding [6].

2 CONTEXT OF THE INVESTIGATION

This worksheet was used in the same introductory level electrical engineering course as its previous version. The course is attended by third semester process and logistics engineering students as well as first semester naval architecture students. It is organized and given by faculty from another department at our university and is taught in a traditional manner with 90 minutes of lecture and 45 minutes of recitation sessions per week. The lecture is attended by about 120 students, while for the recitation sessions students are split into groups of about 20. The course covers the subject of circuit theory with direct and alternating as well as three-phase current. Potential is not part of the standard curriculum. As the curriculum of several courses of study at our university changed, the course was not mandatory for as many students as in the previous year. Except for this change, this year’s course was identical to last year’s course.

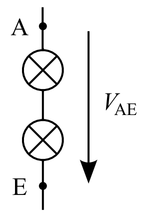
For several years, we have implemented four tutorial worksheets in this course, two of which are in the recitation sessions and two during lecture time with all students and about 15 teaching assistants present. The two worksheets in the recitation sessions are based on hands-on observations that students make in the context of batteries and light bulbs. The course mostly focuses on the quantitative analysis of circuits, while the worksheets focus on qualitative understanding. In the course’s exam, at least one question is similar to the tutorials. Therefore, we are fairly certain that students make an honest effort while working on the tutorial worksheets.

3 DESCRIPTION OF THE MATERIALS USED

In this section we will describe the tutorial worksheet that was developed and the tests used to evaluate it.

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:

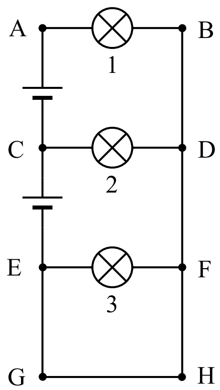


$$V_{AE} = \Phi_A - \Phi_E$$

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.

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 introduced. Start at an arbitrary point on one wire and mark all points and wires with one color that are not separated from this first point by a circuit element. Repeat this process until all points and wires are marked with a color. If possible, use the color red at point A and blue at point E.



Circuit 1

1.2 If wires have no resistance, what is the voltage between two points on the same wire? What is the meaning of regions with the same color?

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.

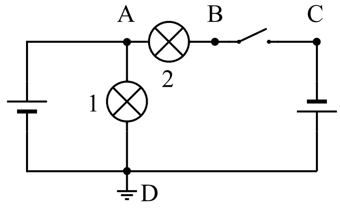
1.6 Rank the bulbs according to their brightness. What relationship between potential difference and brightness can be used for this?

Fig. 1: Excerpt from the beginning of the tutorial worksheet.

Consider the following circuit, which contains identical bulbs, ideal batteries with a source voltage of 1.5 V, a ground and an open switch. The switch stays open until Task 3.

2.1 Colorize all points and wires, according to the color coding introduced in part 1.1.

2.2 Assign a potential to each color.



Circuit 2

2.6 Rank the voltages V_{AB}, V_{AC}, V_{AD} und V_{BC} according to their absolute value. Use the potentials to determine the voltages. Does your answer match the answer you gave in the pre-test?

Discuss your findings with a tutor.

2.7 What is the voltage between both ends of the open switch?

Fig. 2: Excerpt from the middle of the tutorial worksheet.

3.1 Tutorial-Worksheet

Apparently, the previous version of the tutorial was not successful in helping students connect the newly introduced concept of potential with the concepts they already knew. In the post-test they were not only unable to correctly use potential, but their usage of it was also inconsistent with their usage of voltage. They did not recognize both concepts as different representations of the same underlying physical entity, and thus got a better understanding of it, but instead felt that potential was just another concept they had to learn. [1] To overcome these problems, the new tutorial worksheet (excerpts shown in Figures 1 and 2) was modified with two goals in mind that will be discussed in the following.

The first goal when redesigning the worksheet was to make potential appear more useful to students. To achieve this, we presented potential as a *tool* rather than an abstract *concept*. Consequently, the worksheet did not focus on the comparison of the concept of potential to other concepts, such as voltage. Instead, students were shown how to work through an “algorithm” that allowed them to determine the potentials in a circuit. This algorithm is introduced in questions 1.1 through 1.3 in Figure 1.

One of the steps of the “algorithm” to determine the potentials in a circuit is color coding as introduced in question 1.1, Figure 1. In the new version of the tutorial, color coding is used more extensively, as we think it is a very valuable tool for students. Students should learn to quickly identify areas of a circuit that have the same potential, as this helps with understanding a circuit. We believe that color coding can help students to achieve this.

The second goal during the design of the tutorial was to give students more opportunity to apply the concept of potential and connect it to other concepts. Question 1.6 in

Figure 1, for example, asks students to determine the brightness of bulbs, a task that they were asked to do frequently in the other tutorial worksheets to determine the voltage across and/or current through a bulb. Similarly to this question, the identification of short circuits via color coding is discussed.

To further motivate students, the pre-test task shown in Figure 3a, was incorporated into the worksheet. The pre-test was administered right before the tutorial. After the pre-test was collected and the tutorial handed out, students had to fill in their answer to the pre-test in question 0 of the tutorial. This question was a repetition of the pre-test question they had already answered. After the introduction of the potential, students then were confronted with the pre-test circuit again. Now they were guided step by step, how to determine the voltages in that circuit using potentials. We expected (and later confirmed) that virtually no student was able to correctly determine the voltages in the pre-test circuit. With these tasks in the tutorial, many of the students were shown not only a misconception they had, but also an approach how to solve such problems in the future.

3.2 Pre- and Post-Test

To evaluate the effectiveness of the tutorial worksheet, a pre- and a post test was given. Both tests were part of quizzes that were administered at the beginning of a lecture. The first quiz, which contained the pre-test, was given immediately before administration of the tutorial worksheet; the second quiz, which contained the post-test, was given before the next intervention, several weeks after the worksheet was given. Both quizzes contained additional questions that were part of other studies.

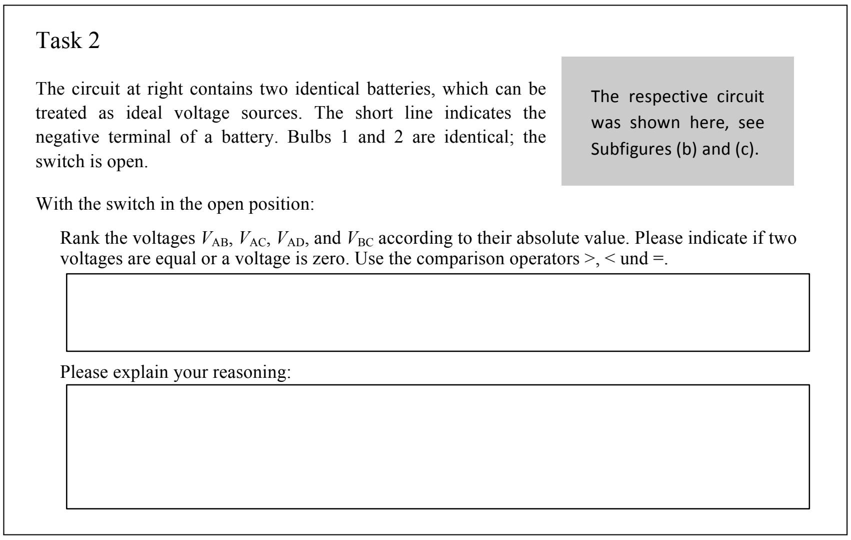
The pre-test consisted of only one ranking question. The post-test contained seven questions. Except for the circuit used, the first question of the post-test was identical to the pre-test question. This question is reproduced in Figure 3, with the different circuits for the pre- and post test given in subfigures 3b and 3c. It should be noted that both circuits are electrically identical if bulb 3, the ground, and node E are ignored. This similarity, however, only becomes obvious if the circuit is fully understood and was not even noticed by some of the teaching staff. In the other post-test questions, students had to rank the potentials at the points marked in Figure 3c and were asked if the voltages V_{AC} and V_{AD} increased, decreased or stayed the same when the switch was closed and if the closing of the switch caused bulbs 1, 2, and 3 to glow brighter, less bright, or equally bright.

For each question, students were asked to shortly explain their reasoning.

4 RESULTS

In the pre- and in the post-test, students were asked to rank four voltages (see Figure 3a). An overview of their answers is given in Table 1. As can be seen, the correct answers (printed in bold face) increased from $0\,\%$ in the pre test to $14\,\%$ in the post test. However, the number of students indicating that the voltage across the open switch is zero ($V_{\text{BC}} = 0$) decreased from $32\,\%$ to $28\,\%$.

As explained above, the worksheet presented here was an updated version that tried to to improve on the shortcomings of last year's version. The first question of the post-test used to evaluate the previous version of the tutorial was identical to this years pre-test question, except that students did not have to rank the voltage V_{BC}. That post-test ranking was answered correctly by $3\,\%$ of the students. If one ignores the voltage V_{BC}, this year $1\,\%$ of the students gave a correct ranking in the pre-test and $19\,\%$ of the


Task 2

The circuit at right contains two identical batteries, which can be treated as ideal voltage sources. The short line indicates the negative terminal of a battery. Bulbs 1 and 2 are identical; the switch is open.

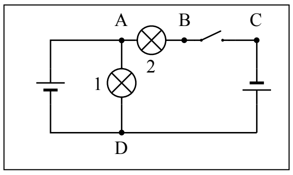
The respective circuit was shown here, see Subfigures (b) and (c).

With the switch in the open position:

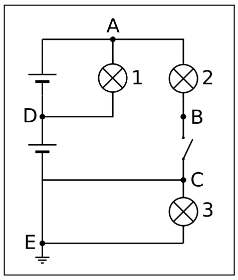
Rank the voltages V_{AB}, V_{AC}, V_{AD}, and V_{BC} according to their absolute value. Please indicate if two voltages are equal or a voltage is zero. Use the comparison operators >, < und =.

Please explain your reasoning:

(a) Question in pre- and post-test.



(b) Pre-test circuit.



(c) Post-test circuit.

Fig. 3: Voltage ranking question from the pre- and post-test. In both tests, the question was identical, except for the circuit used.

Table 1: Overview of answers to the question shown in Figure 3a. Rankings considered correct are printed in bold face.

	Pre-Test		Post-Test	
Ranking	N	Percent	N	Percent
$\mathbf{V_{AC} = V_{BC} > V_{AD} > V_{AB}}$	0	0 %	10	10 %
$\mathbf{V_{AC} = V_{BC} > V_{AD} > V_{AB} = 0}$	0	0 %	4	4 %
$V_{AD} > V_{AB} = V_{AC} = V_{BC} = 0$	18	13 %	19	20 %
$V_{AD} > V_{AB} = V_{AC} = V_{BC}$	7	5 %	5	5 %
other without $V_{BC} = 0$	46	33 %	48	49 %
other with $V_{BC} = 0$	27	19 %	8	8 %
no response	41	29 %	3	3 %
Sum	139	100 %	97	100 %

Table 2: Comparison of measured and a possible distribution of answers to the potential and voltage ranking. N=97

	Potential		
Voltage	correct	incorrect	total
correct	10 %	4 %	14 %
incorrect	4 %	82 %	86 %
total	14 %	86 %	100 %

(a) Measured distribution.

	Potential		
Voltage	right	wrong	total
right	2 %	12 %	14 %
wrong	12 %	74 %	86 %
total	14 %	86 %	100 %

(b) Distribution assuming independence of both concepts

Table 3: Distribution of multiple-choice answers to a post-test question about a short-circuited battery. The correct answer is printed in bold face.

		After closing the switch in Figure 3c, bulb 3 is			
Group	N	brighter	**equally bright**	darker	*no answer*
all students	97	43 %	35 %	6 %	15 %
no ranking correct	79	51 %	27 %	8 %	15 %
any ranking correct	18	11 %	72 %	0 %	17 %

students gave a correct ranking in the post-test. Thus, by comparison, this years tutorial was much more effective, although the percentages were definitely not as high as we were aiming for.

Averaging over the pre- and post-test, 68 % of the students that indicated $V_{BC} = 0$ in the voltage ranking also wrote a reasoning for their answer. Of those students that did not indicate $V_{BC} = 0$, only 37 % gave a reasoning. These percentages were almost identical in the pre- and in the post-test.

Even though they were not asked to do so, at least 21 % of the students had color coded the circuit on the post-test. In the previous year at most 3 % of the students had done so.

In the post-test, students were not only asked to rank the voltages, as shown in Figure 3a, but also had to rank the potentials at points A, B, C, D, and E. We categorized each student's answer to the voltage and potential ranking in Table 2a. As can be seen, 92 % of the students (82 % + 10 %) either gave two correct rankings or no correct ranking. Only 8 % of the students gave one correct and one incorrect ranking. Unfortunately, the low number of students for some of these cases makes it impossible to make a χ^2-test for the independence of the understanding of voltage and potential. Still, we will see how these values would look like for the case of independence of the concepts. Given the total percentage of correct voltage ranking and correct potential ranking is 14 %, respectively, one can calculate a distribution where potential and voltage ranking is independent. This distribution is shown in Table 2b. Comparing these two tables suggests that the ability to answer the voltage ranking correctly and the ability to answer the potential ranking correctly are correlated.

In the last question of the post-test, students were asked how the brightness of bulb 3 changes if the switch in Figure 3c is closed. As the bulb is short-circuited, the bulb's brightness does not change, regardless of the position of the switch. Table 3 shows the distribution of students' answers, split for different groups of students. The students that answered at least one of the rankings correctly, answered much more often correctly than the other students.

5 CONCLUSIONS

The results show a learning gain in the voltage ranking question that is considerable, compared to last year's data. However, the percentage of correct answers in the post-test was still quite small.

The correlation between correct voltage rankings and correct potential rankings supports our claim that helping students understand the concept of potential allows them to better understand the concept of voltage and its use in different circuit set-ups. There were several weeks between the pre- and the post-test in which students participated in regular instruction. This might be seen as the cause for the increase of correct answers in the voltage ranking. However, a large percentage of those students that were able to correctly answer the voltage ranking were also able to correctly answer the potential ranking. The fact that potential was not taught during regular instruction suggests that that the increased understanding of voltage was indeed caused by the tutorial worksheet.

The percentage of students that used color coding increased from 3 % in the post test of last year's tutorial to 21 % in the post test of this year's tutorial. In neither post test, color coding was not mentioned at all. Thus, these students themselves had the idea to use it. In our opinion, this shows that the tutorial was successful in presenting them tools to effectively work with circuits.

The fact that the percentage of correct post-test voltage rankings was so small might suggest that the problem of voltage across an open switch is particularly difficult. Similar tasks were given to students at different institutions and the percentages of correct answers were always quite small. [7] It could also be argued that the misconception that the voltage across open switches is zero is also particularly hard to overcome. In our opinion, this is supported by the fact that students who answered using this misconception gave reasonings much more often than those that answered without using this misconception.

In our opinion, the results presented here show that our approach does work in principle. However the fact that the number of correct answers in the post-test was not very high, makes it clear that further improvements have to be made. Possible changes in the tutorial would be the addition of voltage measurements done by the students. However, most switches are quite small and built as black boxes, allowing one to only measure the voltage across the circuit element's terminals and not the open circuit voltage across the air gap in the switch. Thus, "large" mechanical switches should be used for such exercises so that the open circuit voltage can be measured directly.

ACKNOWLEDGMENTS

We would like to thank Prof. G. Ackermann and his staff for their support of this project by giving us access to their students.

REFERENCES

[1] Timmermann, D. and Kautz, C. (2014) Investigating Student Learning of the Voltage and Potential Concepts in Introductory Electrical Engineering.

[2] McDermott, L. C. and Shaffer, P. S. (2012) *Tutorials in Introductory Physics*. Prentice Hall, updated preliminary 2nd edn.

[3] Kautz, C. (2011) Development of instructional materials to address student difficulties in introductory electrical engineering. *Proceedings of the 1st World Engineering Flash Week*, Lisbon, Portugal.

[4] McDermott, L. C. (1993) Guest Comment: How we teach and how students learn - A mismatch? *Am. J. Phys.*, **61**, 295.

[5] Redish, E. F. (2003) *Teaching physics with the physics suite*. John Wiley & Sons, Inc.

[6] Pride, T. O. B., Vokos, S., and McDermott, L. C. (1998) The challenge of matching learning assessments to teaching goals: An example from the work - energy and impulse - momentum theorems. *Am. J. Phys.*, **66**, 147.

[7] Timmerman, D. and Kautz, C. (2015) Student Understanding of Open Switches and Open Circuits: What Do We (Not) Know? *Proceedings of the Research in Engineering Education Symposium*, Dublin, Ireland, accepted for publication on April 14th 2015.