Development of 3-D Mechanical Models of Electric Circuits and Their Effect on Students' Understanding of Electric Potential Difference

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Abstract

Visualizing physical concepts through models is an essential method in many sciences. While students are mostly proficient in handling mathematical aspects of problems, they frequently lack the ability to visualize and interpret abstract physical concepts in a meaningful way. In this paper, initially the electric circuits and related concepts were taught to tenth grade students traditionally, then, once more, only concepts of electric potential and electric potential difference were taught to them along with 3-D mechanical models of electric circuits developed by the author and finally the effectiveness of the models was assessed. A twelve-item achievement test was given to twenty-two female students from the tenth grade as pre-and post-tests to assess students' comprehension of the concept of electrical potential. We showed that working and, more so interacting, with 3-D electrical circuits in a classroom-improved students' understanding of the idea of electrical potential. Initial experience of using 3-D models of the electrical circuits in a high school physics course is also reported.
Keywords: Analogy, electric potential, electric potential difference, physics education, visualization, 3-D electric circuits

Introduction

Electrical circuits constitute one of the core units of the high school science curricula throughout the world. Among the concepts related to electric circuit, voltage is the more difficult concept for students to comprehend (Mario, 1983). Understanding the relationship between voltage and other basic concepts of electric circuits, such as resistance and current is also hard for students (Pfister, 2004; Vreeland, 2002). Although voltage is a tough concept, understanding it along with other basic concepts such as "electric current," "electric potential," and "electric potential difference" is essential while learning electric circuits (Cohen, Eylon & Ganiel, 1983).

The reason why the electric potential is so hard for students, is that they usually find it unfamiliar, too abstract, and difficult to visualize. Moving from the concrete to the abstract, from observable falling objects to invisible charges, from recognizable forces to imaginary fields, and from potential energy to electric potential is a dramatic change for students (De Jong, 1993). Developing a common sense in these domains is a challenging task for them. Proposing analogies is a common solution science educators use to overcome abstract science concepts. The roles of analogies and their potential for knowledge and learning in science have been reviewed by Duit (1990). Many introductory physics texts use the analogy of water flowing in pipes when introducing concepts in basic electricity and is commonly used

(Minich, 2005) in helping students understand basic circuits. However, the "water and electricity analogy tends to break down when attempting to understand more detailed and explicit understandings of electricity and physics" (Cosgrove, 1995).

In this paper, 3-D electric circuit analogy is introduced as a remedy for higher-level understanding of electric circuits, specifically for electric potential. 3-D electric circuit analogy aims to visualize how electric potential rises due to a battery and drops across the circuit elements. This helps students to understand the principles of electrical circuits. Drawing conceptual analogies to known domains, such as mechanics is a valuable practice in teaching abstract phenomena (Saeli & MacIsaac, 2007). When teaching has a visual dimension, it becomes easy to introduce the information to students. "Visualization constitutes an important part of learning process when instructors try helping students understand what is happening inside electrical circuits and explaining its concepts" (Al-Holou & Ibrahim, 2014).

Significance of the study

A twelfth-grade student, complaining she has never encountered such a problem before, asked about the relationship between the potentials at points K, L, and M, as illustrated in Figure 1. Starting at the 6th grade until the end of the12th grade, students study topics related to electricity several times in Turkey. So it was rather disappointing that the student could not overcome this "simple" problem. The fact that she was able to solve complex problems related to electric circuits– considered by many, including me, as a sign of her being successful–led me to think about the way we teach the concepts related to electricity.

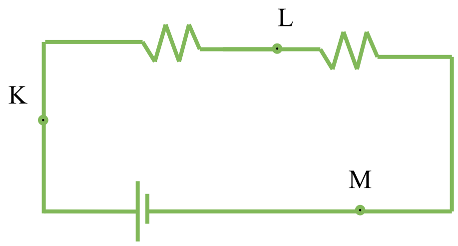

Figure 1. Circuit representing potential at points K, L and M

The problems must be rooted in the fact that instructors tend to attribute success only to solve abstract mathematical problems when teaching the concepts of electrical circuits such as electric potential and electric potential difference. When teaching and assessing the degree of students' learning of physics, teachers' focus leans more towards solving as many problems as possible and less on the conceptual aspects of the topic. This is because of the high intensity of assessments Turkish students take during preparation for high stake national examinations.

Since it is much harder for students to grasp the understanding of the concept of electric potential, when dealing with circuits, physics instructors use instead the concept of electric potential difference, or voltage. Even then, it is still difficult to fully understand these concepts. Therefore, it is better to link them to what the students are already familiar with: the concept of gravitational potential. The potential drop across resistors and electric potentials at various points in an electric circuit can be easily visualized by the use of mechanical models described in this paper. Having students develop such models is expected to enhance understanding of "electrical" concepts, especially that of electric potentials at various points in an electric circuit.

As it was mentioned above, since students cannot always imagine the concept of electric potential, linking it to the gravitational potential, with which the students are already familiar, is considered to be useful. The 3-D mechanical models described in this research can easily visualize the concept of voltage drop across resistors and voltages between various points in an electric circuit. It is anticipated that these mechanical analogies will ease the visualization of the concept of electric potential. It is expected that a course designed to use these analogies will be presented in a more attractive manner and will improve the level of students' understanding of the course material. Specifically, the comparison of electric potentials at various points in an electric circuit (for instance, the question shown in Figure 1) can be taught exhaustively on these 3-D mechanical models.

The analogy of water flow is common among physics teachers to visualize electric circuits. "While such visualizations may be of assistance to the students, the analogy would be difficult and messy to realize as a practical demonstration, as well as being fraught with other complications such as hydrostatic pressure confusing any link between pressure and potential" (Grant, 1996). Moreover, the hydraulic analogy works for basic understanding (Greenslade, 2003) and is usually used in elementary and secondary school physics, but falls apart for higher level physics. The 3-D electric circuit models presented in this paper go further and include an analogy of the concept of potential and potential difference for high school and college physics.

This paper is organized as follows: the introduction section gives a brief summary of the concept of electric potential along with the visualization usage; the second section deals with the significance of the study; Section III describes the 3-D models developed for this study; Section IV presents the method used to verify the usability of the models; Section V outlines the usage of the models; and the final two sections are the results and the conclusion sections respectively.

The 3-D models

The models developed for this paper originate from the study of Minich (2005) who published an article on 3-D wire modeling. Where he compares the 3-D sculptures of electric circuits to the classic hydraulic model of pipes and turbines (Minich, 2005 p. 448). Once that paper was read, the author of current study argued that students will better learn from 3-D wire sculptures if actual, physical lights and batteries are added to them. In this study, just Minich's ideas are improved, new models are developed and the effectiveness of these models on students' understanding of the concept of electric potential is searched.

The basic principle behind the models proposed in this paper is that in these models, voltage is expressed in terms of "heights" or "drops." The 3-D mechanical analogy of the basic electric circuits can be constructed in four different but similar ways.

First, the 3-D model (Figure 2) can be drawn on the blackboard. The height of the battery shows the amount by which the electric potential has been increased. Similarly, the height of the resistors illustrates the voltage drop on them. Since the positive terminal of the battery and the top of resistor R_1, are at the same height, electric potentials at these points are equal. Similarly, since they are situated at the same height, the base of R_1 and the top of the R_2, have the same electric potentials. Using the same approach, one can easily see that the base of R_2 and the negative terminal of the battery are at the same height and hence, have the same electric potentials.

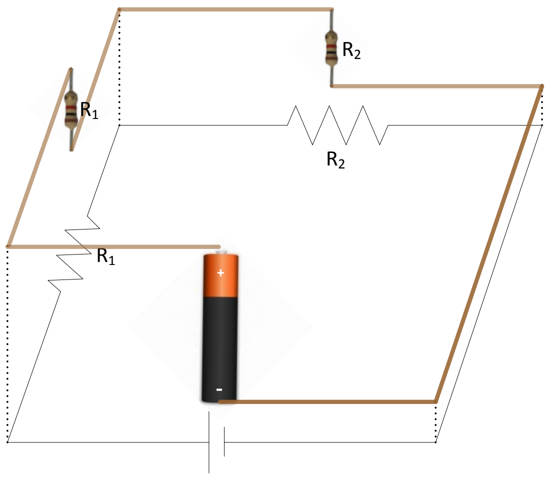

Figure 2. The 3-D model with pictures of the circuit elements

Second, the 3-D model (Figure 3) can be either drawn on the blackboard again, or can be constructed by using wires. It will be informative to match some points on the circuit to its mechanical analogy as shown in Figure 3. Since the points K, L, and M are at the same height, their projections K', L' and M' on the circuits have the same electric potentials. Accordingly, heights of points P, S, and T are the same, and the electric potentials of points P', S', and T' are also equal. Since the relation between heights of points M, S, and V is such that $h_M > h_S > h_V$, the relation between the electric potential at points M', S', and V' are related as $V_{M'} > V_{S'} > V_{V'}$.

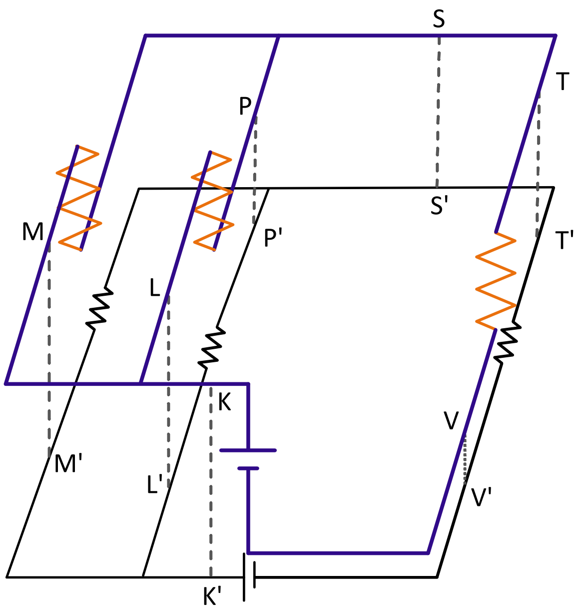

Figure 3. The 3-D model with symbols of the circuit elements

Third, the mechanical analogy can be constructed by using wood, plastic or rods made of any material (Figure 4). Such firm "sculpture" construction can be moved and be used in the class as an instructional tool. Obviously, this is just a 3-D construction similar to the one drawn in Figure 2 and Figure 3.

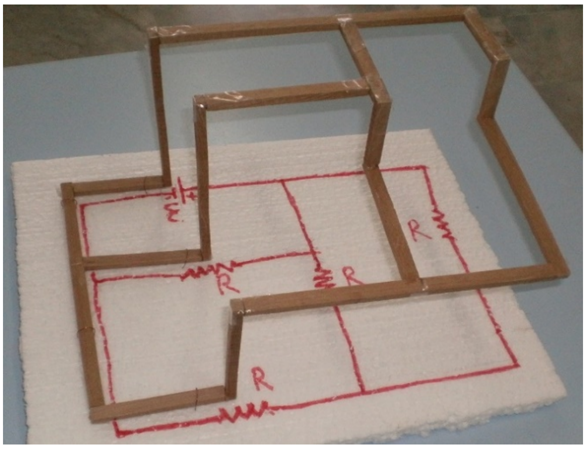

Figure 4. "Sculpture" of a circuit constructed with rods.

Fourth, the mechanical analogy model constructed using real electric circuit elements such as batteries, bulbs, and switches is the most instructionally effective one (Figure 5). When the students who participated in this study were asked about their opinions of the models, the last one was the most favorite.

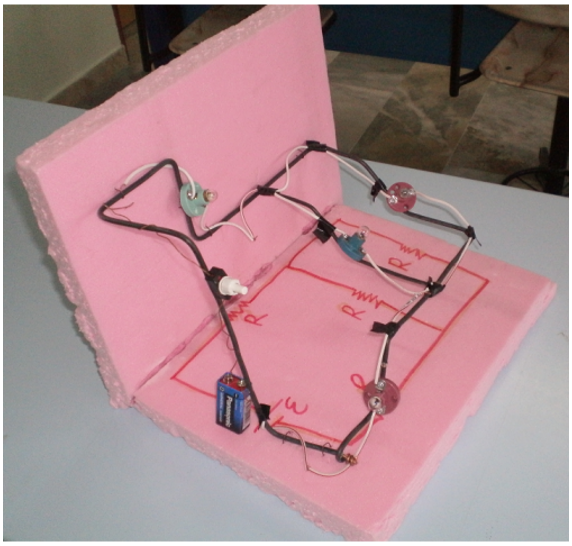

Figure 5. A mechanical analogy model constructed with real electric circuit elements.

These neat 3-D mechanical models assume that the wires themselves have no potential drops. This is a good approximation, since the resistance of a metal wire is so small compared to the resistance of the circuit components that we can ignore them. However, for conceptual understanding, students should be either a) taught that real wires do have a potential drop, but we assume the “ideal wire model” with $\Delta V = 0$ across the wire segments, or b) the potential drop across the wires should be included in the circuit models. If option b) is chosen, then it might be useful to have the potential drops across resistors, and the potential rise across the battery represented in the mechanical analogy by slanting pieces of wood or plastic instead of vertical pieces of wood or plastic. Then each segment representing V across the wires could have a very gentle slant instead of no slant at all, and the voltage drop or rise across circuit components would have a more angled slant.

Methodology

In order to investigate the effect of using the models on students' learning of the concept of electric potential, single group pre-test and post-test research design was used. This is a weak design, however, the aim is only to assess students' understanding of electric potential through the 3-D mechanical models of electric circuits. The sample of the study was 22 female students at tenth grade (16 years old) from an Anatolia high school for girls located at Keçiören district of Ankara, Turkey. Students attending Anatolia high schools get medium scores in the National Placement Exam executed after eighth grade. The author was teaching physics to these students at ninth and tenth grades.

For this study, a 12-question multiple-choice achievement test was prepared including only questions related to the concept of electric potential and electric potential difference. The test questions were selected from high school physics textbooks, and the test was given final form only after having the opinions of two experts from the physics education department at the Middle East Technical University. The experts offered minor changes on the test, such that, one question was replaced with a relatively easy question and two questions including concepts other than electric potential were excluded from the test. The following was one of the questions administered to assess students' understanding of the relation between potentials at different points of two different electric circuits.

The electric circuits I and II given in Figure 6 and Figure 7 are constructed with identical power sources and resistances. Resistances of the connecting wires are negligible.

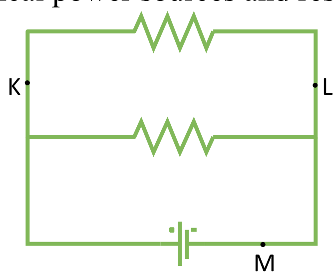

Figure 6. Electric circuit I

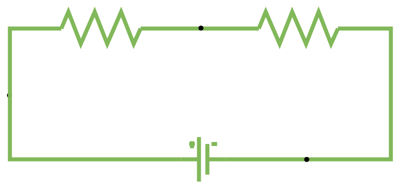

Figure 7. Electric circuit II

The relations between the electric potentials at some points are given as:

I. $V_K = V_N$
II. $V_L = V_P$
III. $V_M = V_T$

Which of the above choices is correct?

A. Only I B. Only II C. Only III D. I and III E. I, II and III

The achievement test was administered by the researcher as a pre-test to the 10th grade students who have already gone over electricity in their curriculum. Later the researcher taught the students the concept of electric potential and electric potential difference once again over the course of one hour using the 3-D models. In the second-class hour, he separated students into groups of three and four students. The groups built various 3-D "sculptures" electric models by using wires. The researcher provided the necessary support to students and answered questions delivered by students regarding the construction of the models. In other words, the researcher was a facilitator and an observer during that class hour. Finally, after three weeks the same achievement test was applied as a post-test. This is enough long time to avoid students remembering answers of the achievement test, and so, preventing the "testing threat" to the internal validity of the study (Fraenkel & Wallen, 1996).

Usage of The Models

Step 1: It is recommended to teach the topic of simple electric circuits in the class the usual way, followed by solving some problems. After the topic is presented, the model should be introduced.

Step 2: The teacher should previously construct an example of the 3-D model as shown in Figure 4 or Figure 5 and then explain how the model is related to what has been instructed before. The instructor should emphasize that the battery increases the potential that drops across the resistors, and the potential is the same everywhere on wires connecting resistors or any other element of the circuit.

Step 3: As always, working in groups enhances the students' understanding and minimizes the teachers' involvement. Therefore, it better allow students to work in groups. Once the groups of three or four students are formed, it is time to construct the 3-D model of the circuit. The initial skeleton frames of the circuit that the students will construct need not to be as complex as described in Figure 2 and Figure 3 so as to make them get familiar with the model building. Students can initially construct the three-dimensional model of the circuits by using wires. It is also necessary for the teacher to give some guidance in the beginning of the building of the model. It is crucial to emphasize that the voltage rise in the 3-D model is represented by the heights of the wire corresponding to the battery.

Step 4: As a quick informal test of the usefulness of the 3-D model building methodology, a circuit similar to the one in Figure 6 can be presented to the students. For this study, the 10th grade students were asked to compare the electric potentials of points K, L, M and N in Figure 8. Most of the students (15 out of 22) could give the correct answer to this question. Parenthetically the achievement test didn't include this question.

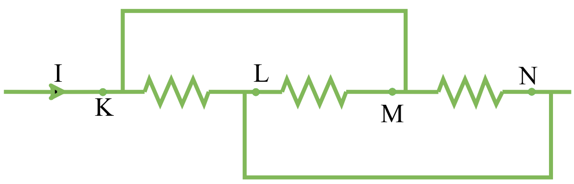

Figure 8. An electric circuit asked to students finding the relationships between potentials at different points

Results

In this section both the results of the observations completed during construction of 3-D electric circuit models and that of the achievement test are reported. Even though the sample of the study is relatively less, it is worth reporting the results of the data collected from this group. The sample is big enough to give some clues regarding the effectiveness of the developed models.

Following results were inferred from having students build the 3-D circuit models. Guiding students in building 3-D models with a single series of resistors was easy. Whereas building 3-D models of relatively complex circuits, including two or more resistors in parallel proved to be challenging. The most frequent mistake was made when students were sculpturing the parallel branches: they built the parallel resistors such that they were parallel to each other but also *parallel* to the table surface. Instead, they had to construct the parallel resistors parallel to each other, but perpendicular to the table surface. Emphasizing that "the potential drops across the resistors" and this potential change is represented as height change in the models, resolved the students' difficulties. Moreover, having built 3-D models of some basic electric circuits, the students seemed to develop enough feel for the electric potential and potential difference to understand more complex circuits. After constructing their models, they stated that they were more confident in establishing the relationships between the potentials at different points in a circuit.

In this study, the data obtained through the pre-test and the post-test were also analysed. The paired-sample t-test was used to determine whether the usage of models was effective in teaching electric potential and electric potential difference. Table I show the results of t-test.

Table 1. Paired-sample t-test results related to achievement test scores

	N	Mean	sd	t	df	p*	r
Pre-test	22	4.72	2.67	-4.99	21	.00	.72
Post-test	22	6.86	2.69				

* p <.05

The t-test results (Table I) showed that students were significantly more successful on post-tests when compared to pre-test scores: $t(21) = -4.99$, $p < 0.05$. Due to the means of the two tests and the direction of the t-value, it is concluded that there was a statistically significant improvement in students' post-test scores. Additionally a high Pearson correlation (.72) was detected between pre-and post-test scores implying the consistency, that is reliability, of the test.

Conclusions and Implications

In this study, the researcher initially taught electric potential by traditional methods than he used the 3-D models and tried to increase students' understanding of the topic. According to t-test results, it can be said that students' level of understanding of electric potential, can be increased one step further through the developed 3-D electric circuit models. Moreover, understanding gained by the students was relatively permanent. This qualitative impression was based on informal conversation with students approximately four months after.

Statistically significant results of t-test implied that having built these models, the students could visualize the potential drops across resistors. The usage of the models during the classes and building the models with students demonstrated that students develop better understanding of the concepts of electric potential and electric potential difference. Because building the 3-D models helped students to visualize the locations and magnitudes of the voltage drops, it helped students to understand why, for instance, the voltage drops across two resistors in parallel are the same or why the voltages in a loop add up to zero. Shortly, it helped students to develop meaningful and more concrete insights into abstract concepts related to electricity.

This study also constitutes an example of modeling in physics and is important in implying that 3-D modeling can be used in teaching the concept of electrical potential difference. This work should also be beneficial to instructors who teach electricity because findings of this study support the idea of the usefulness of model-based learning. On the other hand, the construction of models was a hands-on activity for students. This was amazing, because it was an opportunity for instructors to teach the topic by merging modeling and hands-on activity.

The elementary aspects depicted in this paper have proven to be fruitful in visualizing the electric potential change through the mechanical height change. It is hopeful that other instructors will successfully adopt the 3-D electric circuit models in classrooms. Since core physics concepts do not change a lot when jumped from high school to university, these models can be used in undergraduate physics courses in faculties as well.

Discussion

In textbook by Serway (1996) the author draws two-dimensional qualitative "graphs" showing how voltage changes around a circuit (V is on the y-axis and S, the distance along the circuit, is on the x-axis). This paper proposes a natural extension of this idea, and is, in my opinion, more useful than the two-dimensional graphs. In the Serway textbook, the 2-D graph is used to illuminate Kirchhoff's loop rule; however, these models illustrated Kirchhoff's loop rule more visually. Moreover, these models also illustrate potential energy changes along the circuit (in analogy with gravity as in the motion of a ball along a closed loop), and thus emphasize the connection between electric potential and electric potential energy. This makes the proposed 3-D mechanical models conceptually even richer.

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