Students' Abilities to Solve RC Circuits with Research-based Educational Strategies

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Abstract

One of the main research lines of Physics Education Research is students’ conceptual understanding. Since the ’70s, that line of research has produced not only research papers but also educational material that helps instructors teach physics in a coherent and structured way so that students can understand physics better. We have applied several of these research-based materials in our electricity and magnetism course for physics engineering students and have obtained good results regarding learning gain measured by some standard tests. In this paper, we focus on the effect of students’ understanding of physics concepts on their problem-solving ability from a quantitative perspective. We chose RC circuits given the lack of time devoted to problem-solving in the class on this topic. The results indicate that even though students understand basic concepts such as potential difference, current, capacitance, and resistance, they struggle when trying to apply those concepts to solving RC circuits problems. On the other hand, we also show that students with good quantitative results, at the same time, have good qualitative results.

Keywords: RC Circuits, Physics Education Research, Physics Engineering, Educational Innovation

Introduction

One of the main research lines of Physics Education Research is students’ conceptual understanding [1]. Since the ’70s, that line of research has produced a deeper insight into how students learn as well as educational materials that actively engage students and help instructors teach physics in a coherent and structured way. The results are that students can understand physics better. These strategies are called active learning (AL) activities. They are based on research focused on promoting conceptual understanding through activities that, in general, have students contrast their own ideas against established scientific concepts so that, through a conflict, they participate in constructing their own learning. It has been proved that by using AL strategies, students understand physics concepts better than those who are in a traditional lecture format [2].

Conceptual understanding research in physics has evolved through the years [1]. In the beginning, the research was mostly about identifying the common alternative conceptions that students bring to the classroom. In that stage, there were many studies on different topics in introductory physics [3]. At that time, the first studies were carried out in which researchers focused on instruments (concept tests, CT) to assess those alternative conceptions [4]–[6]. Nowadays, there are still efforts to build concept tests that improve on the previous CT [7], [8] or to build new tests [9].

The main use of conceptual understanding research is to design appropriate AL activities or educational strategies that improve conceptual learning [10]. In the literature, there are many activities which can be used for auditorium format such as Peer Instruction [11], activities for recitation sessions [12] and for classrooms integrated with labs [13], to name a few. In numerous references, it has been published that using AL strategies in the classroom leads to students understanding physics concepts better [14]. However, there are not many studies that relate conceptual understanding to problem-solving skills and/or the use of mathematics in solving physics problems. This research work is an attempt to relate them.

One of the first studies in which there was an effort to relate problem-solving skills to conceptual understanding was one by Leonard et al. [15]. They analyzed different qualitative problem-solving strategies to study the role of conceptual understanding in solving problems. They succeeded to have students develop conceptual understanding and apply it to solving problems. In another study [16], authors focused on comparing students' performance on conceptual understanding and quantitative problem-solving ability in two different educational spaces (Studio and traditional). They presented data in which students in the Studio classroom performed better than those in a traditional environment. However, their abilities to solve problems were the same or slightly worse. Ates and Cataloglu [17] analyzed the effect of reasoning skills on students' conceptual understanding and their problem-solving skills. They found that reasoning skills influence students' problem-solving skills but do not influence conceptual understanding. This result could be indirect evidence that there is no correlation between conceptual understanding and problem-solving skills. In a recent study [18], however, authors analyzed the relationship between conceptual understanding and problem-solving skills in a comparison of two types of instruction; namely, interactive engagement and traditional lecture. They concluded that conceptual understanding does not necessarily support improved quantitative physics problem-solving. As we can see from these studies, there is some evidence that conceptual understanding is not sufficient to develop problem-solving skills.

On the other hand, there are a few studies in which there is an effort to relate conceptual understanding and/or physics success to mathematical skills. Hudson and McIntire [19] analyzed the correlation between mathematical abilities and performance in physics courses. The conclusion is that mathematical abilities are not enough for success in a physics course; however, without mathematical skills, it is very difficult to succeed. In a similar study, Hudson and Rottmann [20] worked with 1403 students enrolled in the first semester of the introductory physics course in which they found a correlation between the final grades and a pre-course diagnostic test of mathematical skills. They found that prior mathematical ability is a primary influence on performance in the course. In a different study, Meltzer [21] analyzed different factors that may affect the conceptual physics learning. He found that mathematical abilities play a greater role than prior physics knowledge for students' learning gains. Buick [22], similar to Hudson's research [19], [20], analyzed the relationship between the initial students' mathematical knowledge and performance in a physics course. He found that there is a correlation between the two variables. In a more recent study, Sadaghiani and Aguilera [23] divided students into two groups. In one of them, the instruction was more conceptual, and in the other, the instruction was more mathematically oriented. They found that there was a slightly higher conceptual gain in the group that promoted concepts. Although these contributions do not agree on all aspects, what they contribute is some evidence that to succeed in a physics course, mathematical abilities are required but not sufficient.

The objective of this study

According to the literature, conceptual understanding is important, because studies show that if focusing only on problem-solving skills, students do not improve in their understanding of physics concepts. Many AL strategies try to overcome this lack of understanding, some of which are very successful in improving the understanding of physics concepts [1]. However, whether conceptual understanding helps develop problem-solving skills is not at all clear. In this contribution, we focus on the effect of students' understanding of physics concepts on their problem-solving ability from a quantitative perspective.

Methodology

The study was conducted at a large private university in Mexico. The students (40) were all part of a section exclusive to physics engineering majors taking a calculus-based electricity and magnetism course. The textbook for the course is "University Physics" by Young and Freedman [24]. Students of the course also attended weekly laboratory sessions where "Tutorials in Introductory Physics" by McDermott and Schaffer [25] was used extensively. All course activities, including the tests, were conducted in Spanish.

The E&M course uses active learning for instruction [26]. During the semester, besides the use of Tutorials, a very successful teaching strategy created by McDermott, et al. [25], the instructor uses Mazur´s Peer Instruction, a conceptual-based educational strategy [11]. He also employs problem-solving activities using collaborative learning, conceptual building activities such as Tasks Inspired by Physics Education Research (TIPER) [27] and educational technologies such as Interactive Simulations for Science and Math (PhETs) from the University of Colorado [28].

For this study, we chose RC circuits. This topic has the two characteristics that we deemed important. Due to time limitations, no time is allotted to problem-solving in this topic, and given its characteristics, problem-solving in RC circuits could be mathematically oriented, not only in the standard calculus that is needed in introductory courses, but also, a simple understanding of differential equations.

In the course, a version in Spanish [29] of the Conceptual Survey of Electricity and Magnetism (CSEM) [6] was administered as a pre- and post-test along with 12 DC circuits questions from the Electric Circuits Concept Evaluation (ECCE) [30]. While all students enrolled in the course participated in the pre-test, the post-test was administered to 34 students. During the course the students took three midterm exams, the second of which evaluated capacitance and capacitors, current and resistance, and DC circuits. The midterm exams included conceptual and quantitative questions.

After reviewing the results of a quantitative problem on RC circuits on the second midterm exam, we began designing a test that would provide data on the conceptual understanding that students developed. After a series of revisions, where both the wording and the content of the questions were discussed and agreed upon, the RC circuits test was administered to students (36) during the last week of the semester.

The RC circuits test was designed with two main objectives in mind: to measure the level of mastery of basic conceptual understanding about the qualitative behavior of RC circuits and to evaluate the ability to obtain and solve relatively simple (although non-trivial) ordinary differential equations in the context of RC circuits. A tutorial-like structure was chosen for the test, with qualitative reasoning followed by problem-solving with conceptual scaffolding. Lastly, we contrasted the results obtained with those originally predicted. See the Appendix.

The RC circuits test was scored independently by the authors, and any differences were discussed and reconciled. Each question was given a score of 0-2 based on the answer and reasoning provided.

To analyze results, we used question number 2 from parts (a) to (e) as a prompt for mathematical-oriented problem-solving skills. We used four different instruments as indicators of conceptual understanding: 1) The second midterm excepting a problem that was on RC circuits; 2) the RC circuits problem in that second midterm; 3) the post-test of the 12 ECCE questions; and 4) the qualitative part of the RC circuits test (See question 1, Appendix).

Results

Figure 1 presents four graphs, one for each of the indicators of conceptual understanding versus the quantitative test. Notice that all the instruments were normalized to 100. Each dot corresponds to a specific student with the conceptual grade on the horizontal axis and the quantitative grade on the vertical axis.

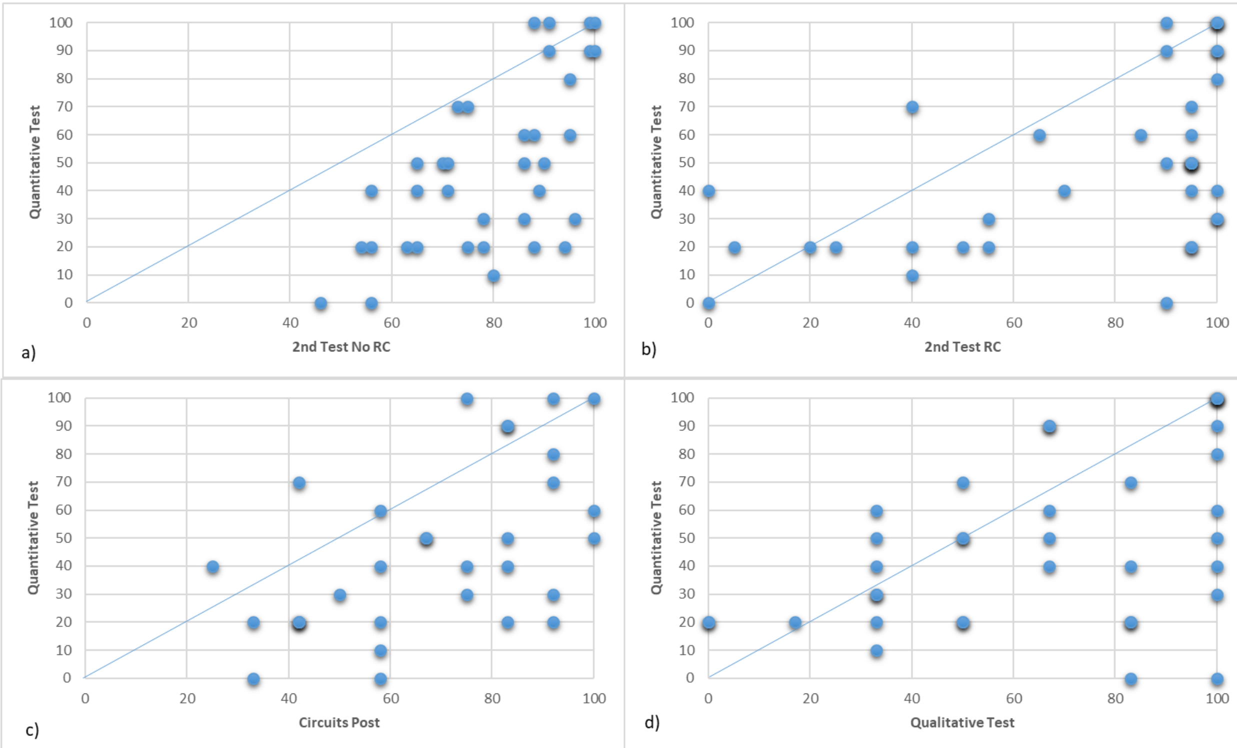

Fig. 1. The quantitative part of the RC circuit test versus the four conceptual understanding measures. A) The second midterm test excepting the RC circuit problem. B) The RC circuit problem in the second midterm. C) 12 ECCE questions as post-test. d) The qualitative part of the RC circuit test.

All of the graphs in figure 1 have the same general features. Most of the students fall in the area under the line, that is, in which the qualitative (conceptual) score is greater than the quantitative score. However, it is clear that graphs c) and d) have more spread. This could be due to the nature of those instruments. Both of them are diagnostic with no penalization to students. On the other hand, graphs a) and b) are results from the midterm exam, which is part of the summative evaluation of students that counts toward their grades. It seems that there is an effect of having a test that counts or not towards students' grades.

To soften this effect, we decided to group the four indicators into one, the conceptual understanding indicator (circuits concepts). To obtain this indicator, we do a weighted average of the four original indicators by valuing the summative instruments twice as much as the formative instruments. This is an arbitrary decision; however, it seems that doing so could give us one indicator that takes into account what is important to students. Figure 2 shows the results of the quantitative test versus the circuits concepts.

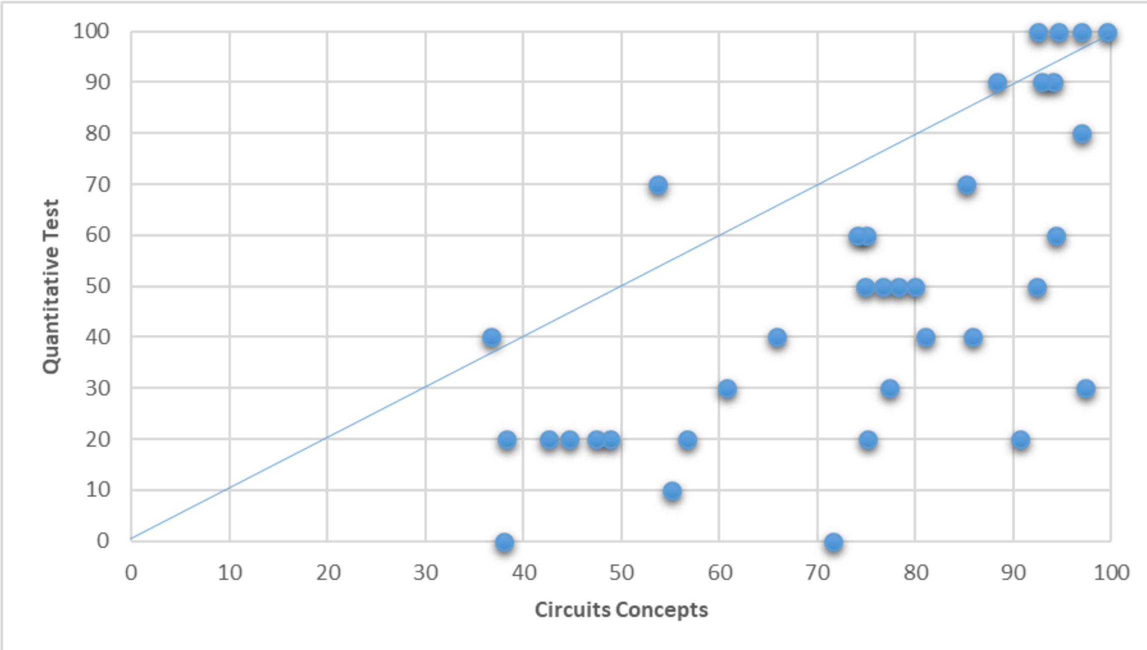

Fig. 2. The quantitative part of the RC circuit test versus the circuit concepts instrument, which is a weighted average of the four indicators shown in Figure 1.

Similar to the general results in Figure 1, those in Figure 2 indicate that, except for a few, all students fall on the region under the line. Some students are above that (quantitative test score greater than circuit concepts score); however, those students have the highest scores in both indicators.

Discussion and conclusions

All four original qualitative indicators measure understanding of concepts related to circuits, particularly, RC circuits. In those indicators (tests), there are questions on the concepts of current, potential difference, resistance, and capacitance, among others. As we mentioned before, this course is structured such that conceptual understanding is emphasized. Some students (Figure 1) grasp these concepts very strongly. The learning gain for this section on the CSEM is 0.52, so the course is quite successful. Of course, some students are left behind; some of them failed the course, probably those who corresponded to the low scores in the conceptual part of Figure 2.

The quantitative part of the RC circuits test (see Appendix) is not emphasized during the course. There are other topics in which problems with quantitative emphasis are taught, i.e., electric and magnetic field calculations or Gauss' and Ampere's Laws problems. Calculus is used during the course but not differential equations. In the quantitative part of the RC circuits test, students not only have to understand how to model the equation but also have to solve the equation. Cui, Rebello, and Bennett [31] mentioned that students need prompting and scaffolding to connect the calculus knowledge with physics problems, so we did it with some success, reflected in the quantitative results shown in Figure 2.

Figure 2 shows that there is a large percentage of students with a high score in the qualitative indicator (44% of students had a score greater than 80%). From those, the spread in scores for the quantitative part is large. On the other hand, all students who have a high score in the quantitative part (i.e., greater than 80%) also have a high score in the conceptual part. It seems that it is required to have a strong conceptual understanding, but this is not sufficient. These results are in partial agreement with McDaniel et al. [18]. In our study, we definitely see that students with good quantitative results, at the same time, have good qualitative results.

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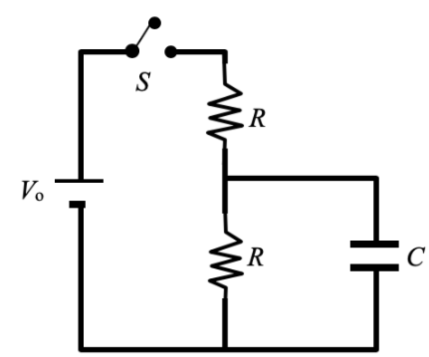
Appendix: RC Diagnostic Test

Consider the circuit shown in the image, where both resistances R are identical, the battery is ideal, and the capacitor is initially discharged. At $t = 0$ the switch is closed. Let I_1 be the current through the resistance that is in series with the switch. Let I_2 be the current through the resistance that is in parallel with the capacitor, and let I_c be the current that "reaches" the capacitor.



1. Qualitative Analysis

   a) Sketch a qualitative graph for I_1 as a function of time for $t \geq 0$. Show clearly the value at $t = 0$ and for $t \to \infty$. Explain your reasoning.

   b) Sketch a qualitative graph for I_2 as a function of time for $t \geq 0$. Show clearly the value at $t = 0$ and for $t \to \infty$. Explain your reasoning.

   c) Sketch a qualitative graph for the capacitor's voltage V_C as a function of time for $t \geq 0$. Show clearly the value at $t = 0$ and for $t \to \infty$. Explain your reasoning.

2. Quantitative Analysis.

a) For all times $t \geq 0$ and using the concept of the sum of voltage, relate the voltage in the battery with the resistances R and the currents I_1 and I_2.

b) For all times $t \geq 0$ and using the concept of potential difference, find a relation among current I_2, resistance R, the charge stored in the capacitor Q, and its capacitance C. Take the derivative of this equation with respect to time to find a relation between the derivative of current I_2 and current I_c.

c) For all times $t \geq 0$ and using the concept of current, find a relation between currents I_1, I_2, and I_c.

d) Using the relations found in (a), (b) and (c), find a differential equation that can be used to determine current I_2.

e) Solve the differential equation integrating the current from the initial time ($t = 0$) up to a certain later time t. Recall that that $I_2(0) = 0$, and that $I_2(t)$ is the expression for the current as a function of time that we wish to obtain.

f) According to the equation for $I_2(t)$ that you obtained in part (e), reflect on whether or not the equation yields values that make sense for $t = 0$ and for $t \to \infty$.

g) Find the voltage in the capacitor V_C as a function of time. Reflect on whether or not the equation yields values that make sense for $t = 0$ and for $t \to \infty$.