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Students' abilities to solve RC circuits with cognitive scaffolding activities

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Students' Abilities to Solve RC Circuits with Cognitive Scaffolding Activities

Abstract

There are many examples of research-based instructional materials that have been shown to help increase students' conceptual understanding and problem-solving skills for most topics covered in introductory undergraduate and some graduate-level Physics courses. The typical Electricity and Magnetism courses often spend little time solving non-trivial quantitative circuits with resistances and capacitances (RC circuits) using calculus and differential equations. Furthermore, the Ordinary Differential Equations (ODE) courses taught to Engineering students focus on mathematical techniques, not on the conceptual understanding of the physical phenomena being modeled nor whether the solution makes physical sense. A recent study indicated that even students with a firm understanding of all relevant concepts struggle when trying to apply those ideas to solve non-trivial RC circuit problems analytically. Building on that work, we designed a team-structured classroom activity based on conceptual cognitive scaffolding to help students construct a mathematical model for an RC circuit starting from the conceptual ideas and solving the differential equation obtained. At the end of the course, we gave the designed RC diagnostic test to the students and compared the results with those obtained from students who had participated in the same class one year before but without the class activity. In this report, we present the analysis of the diagnostic results and compare the similarities and differences between the results of the previous-year students (who had no intervention) and those of the current-year students who had the cognitive scaffolding activity.

Keywords: RC circuits, mathematical modeling, cognitive scaffolding activities, educational innovation, higher education

Introduction

One of the primary research lines of Physics education research is on students' conceptual understanding [1]. Decades of research results have concluded that learning strategies that incorporate the active participation of students in acquiring their knowledge are far more effective than traditional (lecture-based) methodologies to help students gain a conceptual understanding of physical concepts [2]. These strategies that involve the students in the self-regulation of learning employ activities that are called active learning (AL) activities. The main use of conceptual understanding research is to design appropriate AL activities or educational strategies for the improvement of conceptual learning [3].

Most research involving AL has focused on conceptual understanding. There are not many studies that relate conceptual understanding to problem-solving skills and/or the use of mathematics to solve physics problems. In a previous paper, we studied students' abilities to solve RC circuits in the context of a traditional E&M course that used AL strategies [4] extensively. The evidence suggested that while most students had a good qualitative understanding of RC circuits and could explain the overall behavior of the circuitry, they had considerable trouble solving the ordinary differential equation (ODE) that described the system. In this demanding, non-trivial scenario, it appeared that conceptual understanding was necessary but not sufficient to resolve the mathematical problem.

In a recent study [5], the 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. Other studies have found similar results [6].

Regarding the development of problem-solving abilities, Cui, Rebello, and Bennett found that students needed prompting and scaffolding to connect the knowledge of calculus with solving physics problems [7]. With this in mind, we designed and implemented a tutorial-like activity that provided conceptual and metacognitive prompts to students that guided them in modeling and solving the ODE for a non-trivial RC circuit. We used a framework that has been shown to be successful in developing conceptual understanding in physics students [8].

Objective

According to the literature, conceptual understanding does not clearly correlate with problem-solving skills. Furthermore, even students who actively participate in AL strategies have trouble solving ODEs related to RC circuits. In this contribution, the research question is, “What is the impact of a scaffolded problem-solving tutorial on students’ problem-solving abilities from a quantitative perspective, using a previously reported test [4] to measure this in the context of RC circuits?

Methodology

The study was conducted at a large private university in Mexico. The 72 students were all part of a fall 2019 calculus-based Electricity and Magnetism course exclusive to physics and engineering majors. The course was administered following the same design as that reported in the previous study [4]. The textbook for the course was “University Physics” by Young and Freedman [9]. Students of the course also attended weekly laboratory sessions where “Tutorials in Introductory Physics” by McDermott and Schaffer [10] was used extensively. All the course activities, including the tests, were conducted in Spanish.

To measure conceptual understanding, we administered a version in Spanish [11] of the Conceptual Survey of Electricity and Magnetism (CSEM) [12] as a pre- and post-test along with 12 DC circuits questions from the Electric Circuits Concept Evaluation (ECCE) [13]. While all the students enrolled in the course participated in the pre-test, only 63 students took the post-test. During the course, the students had three midterm exams, the second of which evaluated capacitance and capacitors, current and resistance, and DC circuits. The midterm exams included both conceptual and quantitative questions.

After reviewing the results of an RC circuits test administered one year prior [4], we designed an activity that would provide the conceptual understanding and metacognitive scaffolding. The activity guides the students to construct an ODE that models a non-trivial RC circuit and has a level of difficulty similar to the one that is on the RC circuits test. After a series of revisions, where both wording and content of the questions were discussed and agreed upon, the RC Circuits Scaffolded Activity (RCSA) was administered to the 72 students one week before their second partial exam, where that content was evaluated. While the RCSA was not assessed and had no effect on the students' grades, the students did receive feedback on their progress throughout the activity by the instructors. We did not analyze the students' answers to the RCSA.

As with the RC circuits test, we chose a tutorial-like structure for the RCSA, using qualitative reasoning followed by problem-solving with conceptual scaffolding. In the end, we contrasted the results obtained with those originally predicted. See appendix.

During the last week of the semester, the RC circuits test was administered to the students (64) as an extra-credit activity, where credit was given for submitting their test. We followed the same evaluation protocol as in the previous study where 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 the reasoning provided.

We analyzed the results using the same metrics as for the previous study, using question number 2 from parts (a) to (e) in the RC circuits test as a prompt for mathematical-oriented problem-solving skills. We used four different instruments as indicators of conceptual understanding: a) the second midterm excepting a problem that was on RC circuits, b) the RC circuits problem in that second midterm, c) the post-test of the 12 ECCE questions and d) the qualitative part of the RC circuits test.

Results

Figure 1 presents four graphs, one for each of the indicators of conceptual understanding versus the quantitative test. Note 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.

All of the graphs in Figure 1 have the same general feature: most students show a greater conceptual understanding than problem-solving ability. Moreover, Figure 1 shows similar results to those obtained by the students in the year prior who did not do the RCSA [4].

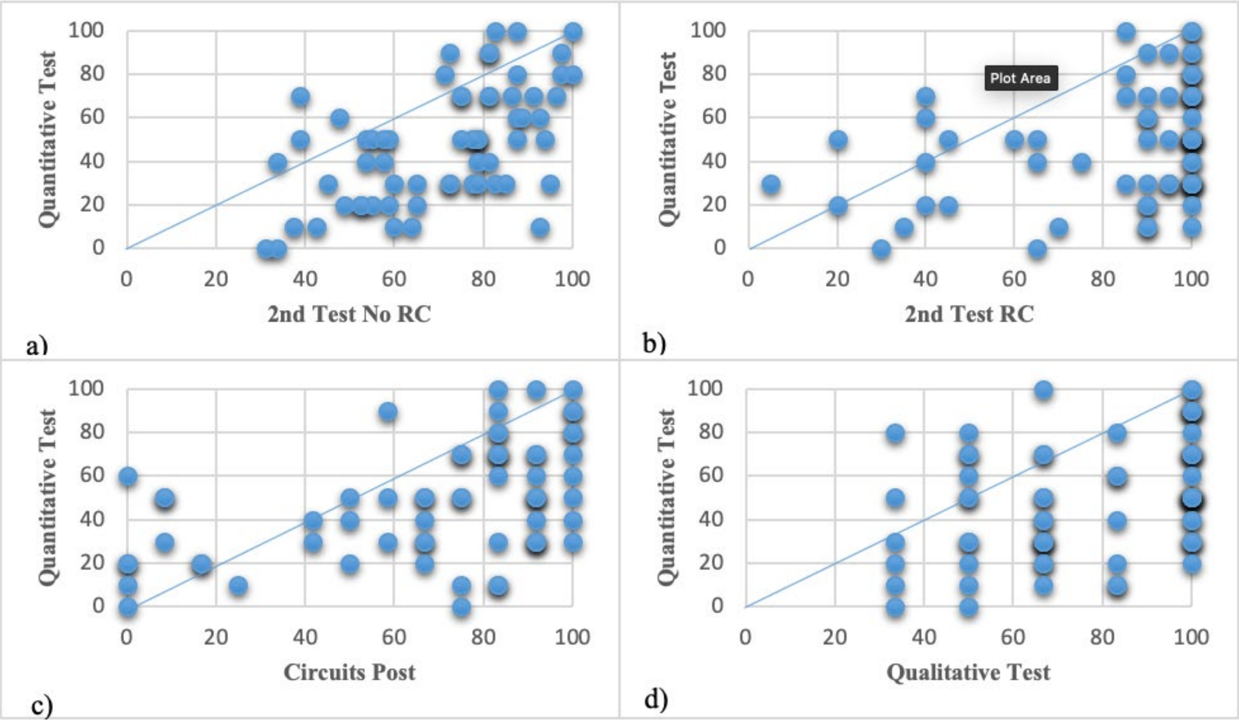

Fig. 1. RC circuit test-quantitative part vs four conceptual understanding measures. a) Second midterm excepting the RC circuit problem. b) The RC circuit problem in the second midterm. c) 12 ECCE questions as post-test. d) RC circuit test-qualitative part.

Figure 2 shows the comparison of the implementation of the RCSA with that of the previous year explicitly. The conceptual understanding indicator is defined as a weighted average of the four original indicators by valuing the summative instruments twice as much as the formative instruments, which takes into account the perceived difference in student commitment between tests that count towards their course grade and those that do not.

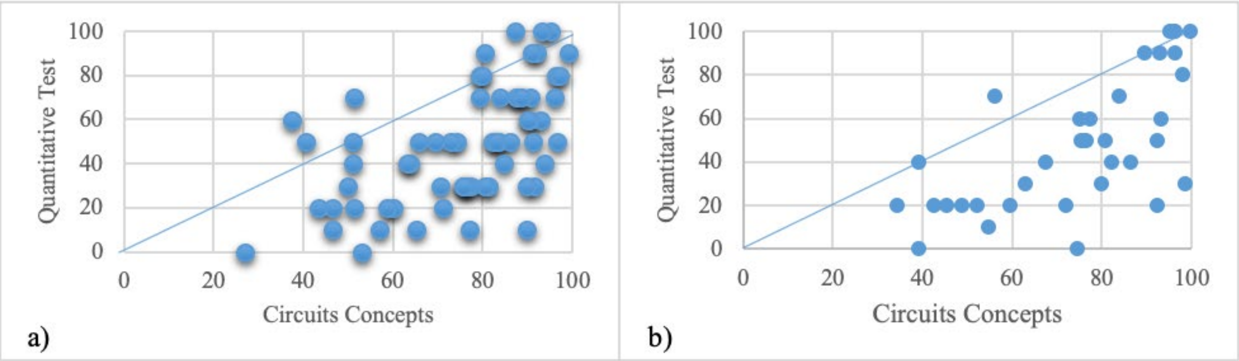

Fig. 2. The quantitative part of the RC circuit test versus the circuit concepts instrument. a) Group that did the RC circuits scaffolded activity (fall 2019). b) Group that did not to the RC circuits scaffolded activity (fall 2018)

TABLE I
PERFORMANCE GROUP AVERAGES

	RCSA	ECCE gain	2nd Midterm exam except RC	2nd Midterm exam RC	ECCE post-test	RC test - Qualitative	RC test - Quantitative
Fall 2018 (N=36)	No	0.52	79.4%	74.2%	68.8%	65.2%	48.3%
Fall 2019 (N=63)	Yes	0.58	70.9%	82.1%	67.7%	75.7%	48.4%

While there does not seem to be a noticeable impact of doing the RCSA on the students' problem-solving abilities as measured by the quantitative portion of the RC test, it is worth noting that the class average for various conceptual understanding measures did improve. The qualitative part of the RC circuits test did improve from 65% to 76% (see Table 1). The performance on the qualitative question on RC circuits on the corresponding midterm exam improved slightly for the group that did the RCSA, as did Hakke's gain [14] in the ECCE for the group that did the RCSA.

Discussion and Conclusions

An E&M course with a pedagogical design that incorporates active learning AL using various strategies [15] has again shown that it is quite successful in helping students with conceptual understanding, including notions related to RC circuits.

In-class activities with conceptual scaffolding have proven to be an effective learning strategy [8], as well as problem-solving in some contexts [16]. For more involved calculus-based problems, Cui, Rebello, and Bennett [7] mentioned in their research that students need prompting and scaffolding to apply the knowledge of calculus to the solving of physics problems. Our intention in designing the RCSA activity was precisely to help the students make connections between physical concepts (voltage, current, resistance, and capacitance) and the construction of ODEs that would have a more tangible meaning. An additional expectation was that this more profound understanding of the equations that modeled the physical system would have a positive effect on the students' ability to solve the equations using simple techniques such as separation of variables. The present study shows no such impact on students' problem-solving skills for RC circuits, although it does seem to reinforce their conceptual understanding. As with our previous research, it appears that conceptual understanding of RC circuits is necessary but not sufficient for constructing mathematical solutions in non-trivial scenarios.

One unstated assumption that is worth re-examining in light of the results obtained is that students are capable of solving a simple ODE by separation of variables by the time they learn about RC circuits. However, the difficulties they have solving quantitative RC circuit problems come from not being able to make sense of the equations that model the system. While many students enrolled in this E&M course that was analyzed were also enrolled in an introductory ODE course, we gathered no enrollment data. We were, thus, unable to examine that for clues.

We sought to adapt a conceptual scaffolding tutorial framework for an activity that would improve the problem-solving skills of students. However, the mathematical proficiency required of the students was higher than that needed in typical E&M courses, and this might have put us in a scenario described by Conlin et al. [17]: a null result that shows how effects fail to generalize to new contexts.

This study suggests that improving problem-solving skills that require refined mathematical tools (ODEs) in E&M requires a more thorough approach than those that have been effective in increasing conceptual understanding. One very appealing alternative is to work in an integrated math-physics course such as the one presented in [18] or [19]. One common problem is the lack of class time available in a typical E&M course for quantitative analyses and solutions of non-trivial RC circuits. An integrated class that covers basic methods for solving ODEs could very well provide the class time necessary for appropriately scaffolded activities that help the student not only connect physics and math but also work out the mathematical solutions.

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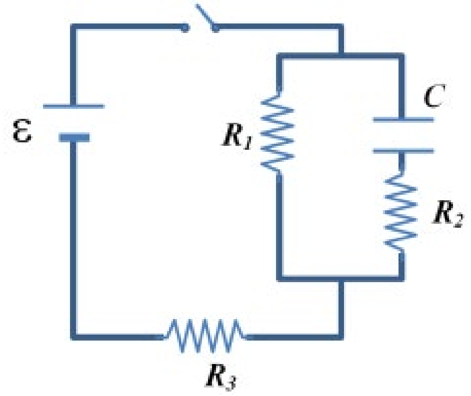
Appendix: RC Circuit Scaffolded Activity (RCSA)

Consider the circuit shown to the right, where the switch is initially open, and the capacitor is discharged. The resistances are identical with value R, the battery is ideal and of voltage ε and the capacitor has capacitance C. The switch is closed at $t = 0$.



I. Review: Qualitative Behavior.

During a previous class activity, you already performed a qualitative analysis of this circuit. Answer the following questions.

a) Immediately when the switch is closed, what is the value of the potential difference V_C of the capacitor? Explain.

b) Immediately when the switch is closed, what are the values of the potential differences V_1, V_2, V_3 across resistances R_1, R_2, R_3 respectively? Explain.

c) A very long time after the switch is closed ($t \to \infty$), what are the values of the potential differences V_1, V_2, V_3, V_C across resistances R_1, R_2, R_3, and the capacitor, respectively? Explain.

d) Sketch qualitative graphs of potential differences V_1, V_2, V_3 across resistances R_1, R_2, R_3, respectively, as functions of time, starting from the moment the switch is closed. Explain.

e) Sketch a qualitative graph of the potential difference V_C of the capacitor as a function of time, starting from the moment the switch is closed. Explain.

II. Quantitative Analysis.

Answer the following questions:

a) Write the equation that relates potential differences ε, V_1, V_3, valid at any time $t \geq 0$, in terms of I_1, I_3, R.

b) Write the equation that relates potential differences $\varepsilon, V_2, V_3, V_C$, valid at any time $t \geq 0$, in terms of I_2, I_3, Q_C, R, C.

c) Write the equation that relates currents I_1, I_2, I_3 through resistances R_1, R_2, R_3 respectively, valid at any time $t \geq 0$. Explain.

d) Write the relation between the current that "arrives" at the capacitor I_C and the charge stored in the capacitor Q_C. Explain.

e) How does I_C compare with I_2? Write the equation that is satisfied by I_2 and Q_C. Explain.

f) Take the equations you found in (a), (b), and (c) and take their derivative with respect to time to obtain the equations that relate the rates of change $\frac{dI_1}{dt}, \frac{dI_2}{dt}, \frac{dI_3}{dt}, \frac{dQ_C}{dt}$.

g) Combine the three differential equations you found in (f) with the one you obtained in (e) to arrive at just one differential equation for I_2. That is, you must obtain an equation in terms of only $I_2, \frac{dI_2}{dt}$ and constants, but no other functions of time.

h) Solve the first-order ordinary differential equation you obtained in (g). Recall that $I_2(0) \neq 0$ (you can show this from your answers to the first page of this activity), and that $I_2(t)$ is the expression for the current through R_2 that we wish to obtain.

i) Is the equation for $I_2(t)$ that you obtained consistent with the qualitative graph for $V_2(t)$ that you gave at the beginning of the activity? Explain.

j) Use the equation for $I_2(t)$ that you obtained as well as the relation you found in (e) to find a function for $Q_C(t)$. Recall that $Q_C(0) = 0$, and that $Q_C(t)$ is the expression for the charge stored in the capacitor that we wish to obtain.

k) Knowing the relation between $V_C(t)$ and $Q_C(t)$, is the equation for $Q_C(t)$ that you obtained consistent with the qualitative graph for $V_C(t)$ that you gave at the beginning of the activity? Explain.