INVESTIGATING THE LEARNING OF RLC CIRCUITS WITH THE AID OF COMPUTER-BASED ACTIVITIES

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ABSTRACT
The purpose of this study was to get some insight about using computational simulations and modeling activities to promote a better students' conceptual understanding of RLC circuits. The theoretical framework adopted was Ausubel's meaningful learning. We elaborated four computer-based tasks, which take into account difficulties commonly experienced by students in learning RLC circuits, to serve as a potential aid to a group of engineering students (experimental group). Significant statistical differences were found between the experimental group students' performance in a conceptual test when compared to the control group, exposed only to the traditional classes. Students' answers to some open-ended questions were also used to assess their conceptual learning. Our results indicate that the computer-based activities, besides facilitating the learning of physics concepts involved in RLC circuits, promoted the interactivity and engagement of the students with their own learning, turning the classroom environment into a privileged space for an active and meaningful learning.

KEYWORDS:
Computational simulation, learning difficulties, RLC circuits, physics teaching.

INTRODUCTION

Electricity has been known as a basic subject in physics education, at all levels, mainly due to its great relevance in our everyday lives, recently restated by Ronen and Eliahu (2000). Probably because of that, simple electric circuits are one of the most researched contents of physics related to students´ learning difficulties (e.g., ref.(Cohen, Eylon and Ganiel, 1983; McDermott and Shaffer, 1992; Duit and Rhöeneck, 1998; Engelhardt and Beichner, 2004)), and many are the studies of alternatives for helping students to overcome these difficulties with the support of the traditional laboratory (e.g., ref.(Shaffer and McDermott, 1992)) and, more recently, with the use of computational resources (Ronen and Eliahu, 1999; Ronen and Eliahu, 2000; Zacharias and Anderson, 2003; Zacharias, 2005; Zacharias, 2007). The persistence on the study of simple electric circuits is justified by the fact that research findings show that, even after formal teaching, many conceptual difficulties, misconceptions and mistaken reasonings are still detected in the students. However, in order to have some understanding of the technological applications that affect our everyday lives, such as telephones, televisions, radios, computers and microwave ovens, it would be desirable that capacitive and inductive circuits were studied, besides circuits with only batteries and resistive elements. Circuits that consist of resistor, capacitor and inductor (RLC[1]) open new perspectives of learning because of their inherent dynamic character, in contrast to simple circuits, in which the attention is focused on the steady states. Moreover, RLC circuits broaden the universe of study from electricity to electromagnetism, and allow connections with other physics subjects. For instance, one may explore the analogy between the spring-mass system and the mechanical resonance phenomenon, turning out the teaching of electromagnetism more attractive to the students, and hopefully more meaningful to them.

[1] We generically called RLC circuits, circuits of type RC, RL, LC and RLC.

Three studies of students´ learning difficulties on RLC circuits (Eylon and Ganiel, 1990; Greca and Moreira, 1998; Thacker, Ganiel and Boys, 1999) and some new possibilities of theoretical and experimental approaches (Faleski, 2006; Ross and Venugopal, 2006; Hellen and Lanctot, 2007; Magno, Araújo, Lucena, Montarroyos and Chesman, 2007) were found in the literature. However we did not find proposals regarding the use computational resources as an aid to overcome the students' difficulties with RLC circuits. This motivated us to start a project with this goal. The aim of this first study was to investigate possible benefits of the use of computer-based activities to help students to understand the dynamic behavior of the electromagnetic quantities involved in RLC. In this paper, results of a pedagogical experience made with engineering students of a Brazilian public university are presented.

PRIOR STUDIES

Among the various studies reported in the literature about the use of computer-based simulations in the teaching of physics, we outline three that deal with contents of electricity (Ronen and Eliahu, 2000; Finkelstein, Adams, Keller, Kohl, Perkins, Podolefsky and Reid, 2005; Zacharias, 2007).

Ronen and Eliahu (2000) developed a study to investigate the role of computer-based simulations as instructional resource to help students on filling the existing gap between theory and reality. The study involved two groups of students who performed two tasks: to draw a diagram of a real circuit and to build real circuits which would work according to certain specifications. One of the groups had at its disposal an open simulation environment conceived to help them in the development of such tasks. Significant differences were found between the groups that solved the tasks with or without the simulations. The use of simulations, besides motivating and increasing the confidence of the students, contributed to improve their ability in designing and interpreting diagrams that represent real circuits.

Finkelstein, Adams, Keller, Kohl, Perkins, Podolefsky and Reid (2005) investigated the possibility of substituting a computer simulation for real laboratory equipment in the teaching of simple electric circuits. The students who used computer-based simulations instead of laboratory equipments had better performance in the resolution of conceptual questions on simple circuits and, surprisingly, developed better ability of handling real components. In the same subject, Zacharias (2007) has shown that the integration between real experimentation and virtual experimentation in the teaching of simple electric circuits can favor a better conceptual understanding of the students in comparison to students who use only real experimentation.

Regarding learning difficulties in RLC circuits, we present in Table 1 a synthesis of the conceptual and reasonings difficulties that students usually have (Eylon and Ganiel, 1990; Greca and Moreira, 1998; Thacker, Ganiel and Boys, 1999). Also various misconceptions are pointed out in these references and summarized in Table 2.

LOOKING FOR A MEANINGFUL LEARNING

Our purpose in using computational simulations and modeling activities was to offer potential aids to help students achieve meaningful learning. According to Ausubel's theory (Ausubel, 2000), it occurs when the new information interacts – nonarbitrarily and nonverbatimly - with relevant anchoring ideas (*subsumers*) present on the individual's cognitive structure. Two basic conditions must be satisfied for meaningful learning: i) the student must have in his/her cognitive structure appropriate subsumers and ii) the learner should present a disposition to link the new material to her/his cognitive structure in a substantive and nonarbitrary way.

Regarding the first condition, the learning material developed has close connection with the subject learned before in the course and specially takes into account difficulties commonly experienced by students in learning RLC circuits pointed out in the literature. For the second condition, we tried to motivate the students with computer-based activities. At the end, to check whether the students had in fact achieved meaningful learning instead of rote learning, we applied conceptual multiple choice tests and open-ended questions rather than quantitative re-hashes of homework-type problems.

Table 1 – Synthesis of the usual students´difficulties in the study of RLC circuits (Eylon and Ganiel, 1990; Greca and Moreira, 1998; Thacker, Ganiel and Boys, 1999).

	Concepts	Difficulties
RC Circuits	Electric current	▪ Understand that during the processes of charging and discharging the electric current magnitude decays exponentially. ▪ Take into account the spatial conservation of the electric current.
	Electric charge	▪ Understand the charging and discharging processes of the capacitor. ▪ Understand the relation between electric charge and electric current.
	Potential difference	▪ Relate the potential difference across the capacitor to the amount of charge stored and the potential difference across the resistor to the magnitude of the electric current.
LC and RLC Circuits	Electric charge and electric current	▪ Relate the magnitude of the electric current to the amount of electric charge stored in the capacitor in terms of time. ▪ Identify the direction of the magnetic field lines in the inductor during the processes of charging and discharging of the capacitor.
	Electromagnetic field	▪ Understand the behavior of the electric, magnetic and electromagnetic energies during a complete oscillation.

Table 2 – Typical misconceptions that students have in the study of RLC circuits (Eylon and Ganiel, 1990; Greca and Moreira, 1998; Thacker, Ganiel and Boys, 1999).

Students…
… think that the current is consumed when passing through an electric resistance (Thacker, Ganiel and Boys, 1999).
… believe that in an RC circuit: a. the electric current is constant in both sides of the capacitor, as long as the potential provided by the battery and the electric resistance remain constant (Eylon and Ganiel, 1990); b. the magnitude of the electric current is zero, because the capacitor represents a break in the circuit (Eylon and Ganiel, 1990; Thacker, Ganiel and Boys, 1999); c. when the capacitor is completely charged the electric current will remain constant and non-zero (Eylon and Ganiel, 1990); d. the order of the elements matters (Thacker, Ganiel and Boys, 1999); e. the electric charges jump from one plate of the capacitor to the other (Thacker, Ganiel and Boys, 1999);
… mechanically reproduce the bar graphs which are in the textbook on the stored energies in a LC circuit, not being able to represent even the direction of the magnetic field lines in the inductor during a complete oscillation (Greca and Moreira, 1998).
… develop a mechanical reasoning based on formulae, not wondering about what physically happens in RLC circuits (Greca and Moreira, 1998; Thacker, Ganiel and Boys, 1999).

RESEARCH METHODS

The research question was: the use of computational simulation and modeling can make the students have a better conceptual understanding of the dynamic behavior of the electromagnetic quantities involved in RLC circuits in comparison to the understanding of students only exposed to traditional teaching?

The study took place during the teaching of RLC circuits in the Physics II-C course (electricity and magnetism for engineering students) offered by the Department of Physics of the Federal University of Rio Grande do Sul, Brazil, during the second semester of 2005, in a total of four classes of 1h40min each.

Research design

We decided for a quantitative evaluation with a conceptual multiple choice initial and final test, and a qualitative evaluation, having as basis the responses given by the students in the printed guides collected at the end of the classes, and in a question of an examination at the end of the course. To evaluate how the students feel about the computer-based activities, we planned to collect written testimonies after the end of the course via electronic mail.

The study was developed according to a non-equivalent control group research design (Campbell and Stanley, 1963) shown in Table 3, because there was no possibility to random assignment. The experimental group was formed by a class with 26 students, and 31 students of two other classes was taken to compose the control group. All classes used the same textbook and performed the same lab experiments.

Table 3. Research quasi-experimental design

	Design
Experimental group	O_1 X O_2
Control group	O_1 O_2
O_1 initial test; O_2 final test; X computer-based activities	

Instructional materials

We chose software Modellus because "the user can write mathematical models, almost always the same way as he would on paper" (Teodoro, Vieira and Clérigo, 2007) facilitating the construction of computer-based models by the students themselves. Another important aspect is that Modellus allows the interaction of the students with the computer-based models in real time, allowing, also, the observation of multiple (conceptual) experiments simultaneously (Teodoro, 1998).

Based on the learning difficulties presented in section II (Table 1), we established the objectives to be achieved by the students after the teaching of RLC circuits (Table 4) and we conceived three computer-based simulation activities and one modeling[2] activity in order to help them to achieve these objectives[3].

[2] We call computational activities those activities in which the student has autonomy to insert initial values to the variables and to modify alter parameters, but do not have autonomy to change the core of the computational model modifying the most basic elements, iconic and mathematical, which constitute it. In computational modeling, besides being able to act upon the variation of initial parameters and values, the student has access to the basic elements. He/she can also build his/her own computational models and create ways to represent them.

[3] Available at: http://www.if.ufrgs.br/cref/ntef/circuitos.

In our models, representing RLC circuits, as usual, we assume that the resistors are ohmic, the conductive wires and the batteries have negligible electric resistance. The first computer-based simulation activity performed by the students on an RC circuit is illustrated in Figure 1 and described in Table 5. In order to explain the behavior of the curve in the graph charge versus time shown in Figure 1 – in which the capacitance was suddenly decreased, when the capacitor was near to its maximum charge – the students must perceive that: i) before this change the potential differences across the capacitor and in the battery is almost the same; ii) when the capacitance is suddenly decreased the potential in C turns out greater than the potential difference provided by the battery; iii) the electric potential of the capacitor plate with charge +q becomes greater than the electric potential of the positive terminal of the battery and the electric potential of the plate with charge –q becomes smaller than the electric potential in the negative terminal of the battery and iv) this changes to the opposite side the direction of the electric current in the circuit and yield a discharging process in the capacitor until the electric potentials in the capacitor and in the battery becomes the same again.

The third simulation questioned about the behavior of the electromagnetic energy in a series RLC circuit, without battery but with the capacitor fully charge at the beginning. All the students previewed that electromagnetic energy would decay exponentially with time. However, when interacting with the computer-based simulations students perceived differences between the expected exponential decay and the observed energy dissipation curve (Figure 2). The simulation also gives to them the possibility to change the position of a switch – to open and close the circuit – and to vary the value of R. By analizing, then, the electric, magnetic and electromagnetic energy as function of time the students were able to associate the "plateau" observed on the energy dissipation curve to the moments of zero electric current in the RLC circuit and progressively they were able to explain it. To some students the analogy with a mechanical system – a projectile vertically thrown with air resistance – contributed to a better understanding of this.

Details of the expressive activity of computational modeling are shown in Table 5. The students were free to actually change the mathematical models to reflect different models of the behavior of the RL circuit components. We expected that the students would write in Modellus, typically, what is in Figure 3, and create cursors that would allow changing the values of R and L continually[4].

The instructional material includes printed guides for the students conceived to be used according to the POE (Predict, Observe, Explain) method proposed by White and Gunstone (Tao and Gunstone, 1999; Zacharias, 2005). Initially the students are asked to predict the dynamic behavior of some electromagnetic quantity involved in the RLC circuit presented in the computer screen. Next, they have the possibility to interact with the computational resource in order to generate results to observe what effectively happens, and then they are asked to explain the divergences and convergences between what was predicted and what effectively happened.

[4] In case the students have not yet created any models that involve differential equations before, one may, as we have done, give them a model for the RC circuit, so that they understand and modify it in such a way to turn it adequate for a RL circuit.

Table 4 – Objectives to be achieved by the students in the study of RLC circuits.

Given a	The student should…
RC circuit	1. understand the charging and discharging processes of the capacitor; 2. notice that the magnitude of the electric current decays exponentially with time during the charging and discharging processes of the capacitor; 3. grasp that the electric current is not consumed along the circuit; 4. grasp that the magnitude of the potential difference: a) in R, is proportional to the magnitude of the electric current and b) in C, is proportional to the amount of stored charge in the capacitor;
RL circuit	5. be able to notice that the magnitude of the electric current in the circuit does not reach its maximum value immediately;
LC circuit	… be able to 6. interpret the dynamical behavior of the amount of charge stored in the capacitor; 7. interpret the dynamical behavior of the magnitude of the electric current; 8. grasp the dynamical behavior of the electric field between the plates of the capacitor to the magnitude of the electric current; 9. grasp the dynamical behavior of the magnetic field in the inductor to the amount of electric charge stored in the capacitor;
LC or RLC circuit	10. be able to notice the dynamical behavior of the electric, magnetic and electromagnetic energies

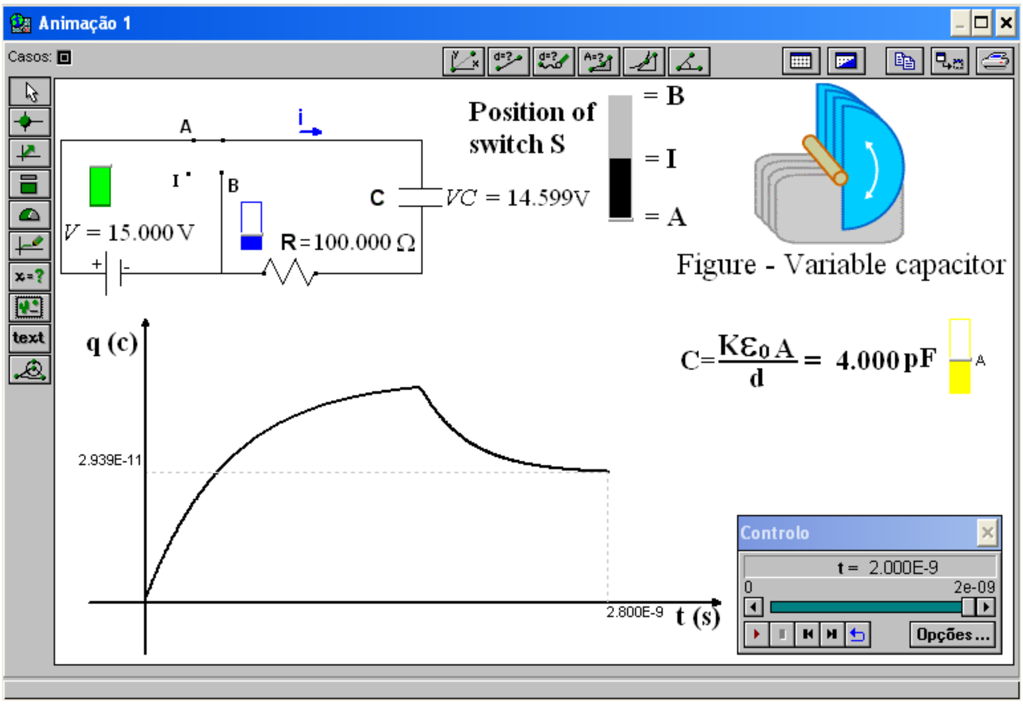

Figure 1 – Illustrative screen of an activity performed by the students.

Table 5 – Details of a computer-based simulation on a RC circuit.

General description	Running the simulation, the charging of the capacitor begins and the graph charge versus time is drawn, allowing for the student to study the dynamical behavior of the amount of electric charge stored in the capacitor when changing the capacitance of the capacitor C, the potential difference provided by the battery and the electric resistance in resistor R (Figure 1). It is also possible to observe the discharging of the capacitor when changing the position of switch I.
Activity goals	Given a RC circuit the student must: - understand the behavior of the charge on the capacitor when it is charging and discharging; - be able to physically describe the graph of the amount of charge stored in the capacitor versus time, when the potential difference provided by the battery or the capacitance of the capacitor are suddenly altered during the charging process of the capacitor; - notice that the magnitude of the electric current decays exponentially with time during the processes of charging and discharging of the capacitor.
Concepts	Electric charge, electric current, electric resistance, potential difference and capacitance.
Questions proposed to the students	Attention: answer items "a and b" before running the model. Consider that the capacitor C is being charged. a. Sketch the curve which represents the charge of the capacitor in terms of time for a situation in which the potential difference provided by the battery V is suddenly: i) increased ii) reduced, when capacitor C is in the beginning of the charging process iii) reduced, when capacitor C is close to its maximum charge. b. Sketch the curve which represents the charge of the capacitor in terms of time to a situation in which the capacitance of the capacitor is suddenly: i) increased ii) reduced, when capacitor C is being charged iii) reduced, when capacitor C is close to its maximum charge. In this model it is possible to vary the electric resistance of resistor R, the potential difference provided by the battery V and the capacitance of capacitor C by altering the area A (through the respective rolling bars close to them). c. Run the simulation, and manipulate values V and C trying to create the graphs drawn in items "a and b". Explain the differences between the graphs observed and the ones predicted by yourself, in case there was a difference. d. What happens to the variation rate of the amount of charge q(t) stored in the capacitor during the process of charging (switch I in position A) in a situation in which the electric resistance in R is suddenly: i) increased ii) reduced. e. Sketch the graphs of the variation rate of the amount of charge q(t) stored in the capacitor during the processes of charging and discharging. Which physical quantity this variation represents?

The activities require constant interaction of the students with the computer, of the students among themselves and, occasionally, with the teacher. The interaction with the simulations occur with the use of ''scroll bars'' and ''buttons', as well as by changing the initial values and/or the value of some parameter of the model.

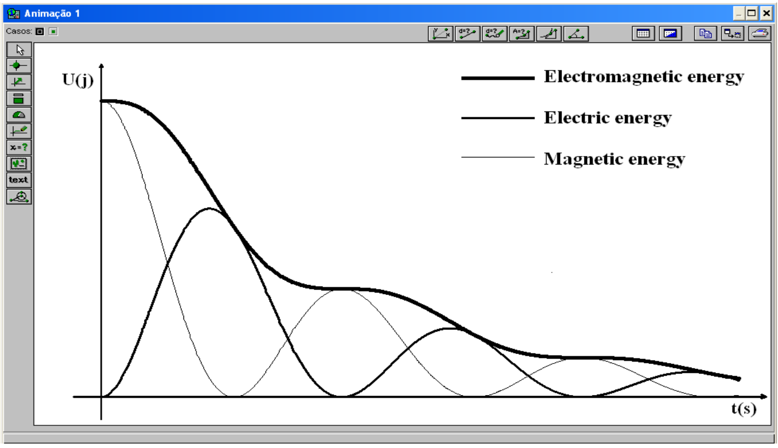

Figure 2 – Screen of a computer-based simulation representing an RLC showing the electromagnetic, magnetic, and electric energies as a function of time.

Table 6 – Details of the computer-based modeling activity proposed to the students

General description	In this activity we provide the mathematical equations which constitute a computational model of an RC circuit (Figure 3), in order to help students to construct a computational model of an RL circuit that represents the behavior of the electric current, of the inductance and of the potential difference across the resistor and across the inductor as a function of time
Objectives of the activity	Given an RL circuit the student should be able to: - notice that the magnitude of the electric current in the circuit does not reach its maximum value immediately; - identify the dynamical behavior of the magnitude of the electric current and of the potential difference across R and L, as well as the inductance L.
Concepts	Electric current, potential difference and inductance
Questions proposed to the students	a) the model window shown in Figure 3 is one of a model of an RC circuit. Based on it, build a model of an RL circuit. b) Insert in the Animation window of the model built, a bar to vary the inductance in the inductor L. Afterwards, discuss the alterations in the electric current and in the potential difference across R and in L when altering the inductance in L.

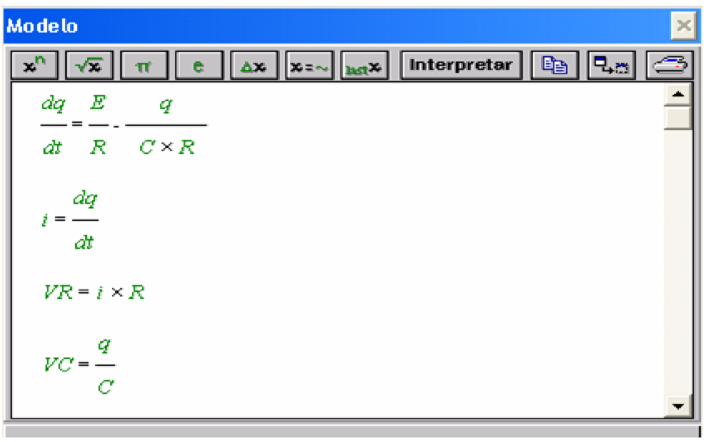

Figure 3 – Mathematical model for the RC circuit written in Modellus.

Procedures
During the four classes of this study the students of the experimental group worked with the computer-based activities in pairs in a computer laboratory, with one PC per pair. We started each class with a brief theoretical exposition (less than 30 min) about the most important concepts involved in the activities to be worked and, in the remaining time, the students interacted with the computational resources to answer questions formulated as driven queries or ‘‘challenges’ in the printed guides. At the end of each class, the students were asked to hand back just one answered guide per pair, for evaluation purposes. From the second class on, before the theoretical exposition, we coordinated a discussion with all the students about the activity worked in the previous class.

The students from the control group were exposed to the traditional expositive classes. Both groups, also, had traditional experimental classes.

Instruments
The purpose of an initial test for experimental and control groups was to serve as a covariate in the analysis of the final test results. We chose a conceptual test about simple electric circuits consisting of 13 multiple-choice questions designed by Silveira, Moreira and Axt (1989). Content validity was established by a group of physics teachers when the test was created and we applied it to 110 engineering students from UFRGS in 2005 to obtain the reliability coefficient of the instrument (Cronbach's alpha), resulting in 0.85. See appendix for a sample of the test' items.

None of the studies mentioned in section II presented a diagnostic test to evaluate whether the students had scientific conceptions on electromagnetic quantities typical of RC, RL, LC and RLC circuits. Then, based on the difficulties pointed out in the literature (Eylon and Ganiel, 1990; Greca and Moreira, 1998; Thacker, Ganiel and Boys, 1999), we constructed and validated another test with 17 items. In the appendix, we are showing, as examples, two items of this test. Each item has five alternatives, one of which is coherent with scientific conceptions, while the other four might be coherent with misconceptions or mistaken reasoning that students usually commit regarding these circuits (Table 1). The test was previously examined by a group of four physics teachers experts in the subject to obtain content validity, and then applied to 110 engineering students from UFRGS intending to calculate the reliability coefficient of the instrument, which resulted in 0.80. After this study, we developed a new version (version 1.1) and applied it to 137 students to recalculate the Cronbach alpha coefficient, which resulted in 0.81. The test ended up with 15 items.

RESULTS AND DISCUSSION

Data has been collected with the application of the initial test (Silveira, Moreira and Axt, 1989) on simple electric circuits on the first day of classes of the course and the final test at the last day of the course. The comparison between the experimental and the control groups in these tests are shown in Table 7. As there is a difference between these mean scores, with statistical significance level measured through the t-test as $p < 0,001$, we carried out an analysis of the Variance and Covariance – NOVA/ANCOVA (Finn, 1997) – using as covariable the data collected with the initial test (Silveira, Moreira and Axt, 1989). The adjusted means in the final test for experimental and control groups are also shown in Table 7.

Table 7– Comparison of mean score between experimental and control groups in the initial and final test. The last three columns show the adjusted means.

Group	**Initial test (13 items)**			**Final test (15 items)**					
	Mean total score	Standard deviation	Right answer %	Mean total score	Standard deviation	Right answer %	Adjusted mean final test	F	Statistical Significance level
Exper.	4.8	2.2	37%	12.4	1.5	82%	12.7	21.90	0.000
Control	7.0	2.1	54%	9.5	3.2	63%	9.2		

Based in these results we concluded that the performance on the conceptual test of the students who worked with the computer-based activities (experimental group) on the conceptual test was better than the performance of the students who were submitted only to traditional teaching (control group).

In order to attempt to probe the details of the reasoning students were using, we analyze students' written responses. Here we comment just the results of this analysis for a question of the exam, namely a question related to a sudden reduction of the potential difference across the capacitor, shown in Fig.1, which is propitious for a conceptual reasoning. The responses of the 26 students were analyzed by two of us and were categorized according to the kind of argument that they used: conceptual or formula based one. The students (except two) used qualitative arguments instead of formula based one, and most of them (15 in 26) got the correct answer to this question with correct reasoning. It seems to us that the computer-based activities fostered a conceptual reasoning instead of the rote use of formulae, which is very common in our students.

Another important result is that during the classes we observed that in order to answer the conceptual questions presented in the printed material, the students from the experimental group interacted constantly with the computational resources to generate and test their hypothesis. They also interacted among each other either to find a consensual answer among them all or to help a classmate having difficulty. This certainly contributed in the understanding of the students of the dynamic behavior of physical quantities present in the RLC circuits. Below are two samples of students' statements about the experimental treatment:

> "*In the simulations it was possible to change the circuits' parameters and see what happened instantaneously. This ended up illustrating the situation, which was good for the understanding, specially of graphs."* (Student 9).
>
> "*I positively outline the greater understanding of the subjects approached in class, which become much clearer during the computer-based classes and the interactivity that these classes promote, bringing the student closer to physics*" (Student 3).

Based on our class notes and on the opinion of the students about the experiment, we believe that in the present study we promoted situations capable of stimulating the interaction and the engagement of students to their own learning, making the classroom environment into a privileged space for active and meaningful learning.

CONCLUSIONS

Much research has been done to investigate the learning of simple electric circuits however there is a lot to be done with respect to the learning of RLC circuits. We propose to approach this subject using computer-based activities (simulation and modeling ones) as a potential aid to help students to achieve a meaningful learning of the dynamical behavior of the circuits. The quantitative results on a conceptual test show that there was statistically significant difference in the performance of the students who worked with the computer in comparison to the performance of the students who were exposed only to the traditional teaching. The analysis of the students' written responses to open-ended questions shows that most of the experimental group students got the correct answer with correct reasoning. Then, the answer to the research question is yes, the use of computational simulation and modeling can promote a better students' conceptual understanding of the dynamic behavior of the electromagnetic quantities involved in RLC circuits in comparison to that of students only exposed to traditional teaching. However there is a limitation for this conclusion: it is not possible to disentangle the effects of i) working with the computer-based activities; ii) increasing students' interactions with themselves and with the teacher, and iii) making the students active subjects of their own learning.

Anyway, the results shown in this paper seem encouraging to us, and we have as future perspective to develop a study with the objective of investigating the integration between the proposed computer-based activities and experimental ones.

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APPENDIX:

Sample test items about simple circuits (Silveira, Moreira and Axt, 1989)
The circuit shown in Figure 1, R is a resistor, and L_1 and L_2 represents light bulbs. In this circuit:

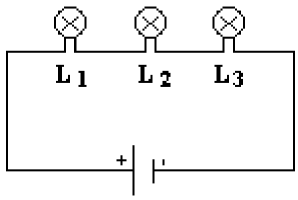

Figure 1

a. L_1 e L_2 have the same brightness.
b. L_1 brights more than L_2.
c. L_2 brights more than L_1.

Sample test items about RLC circuits.

1. The circuit shown in Figure 2 is made of a resistor R, a capacitor C initially discharged, an electric switch S and three ammeters (A1, A2 and A3). When closing switch S, which of the alternatives best represents the magnitude of the electric current i_1, i_2 and i_3 measured in the ammeters, while the capacitor is being charged?

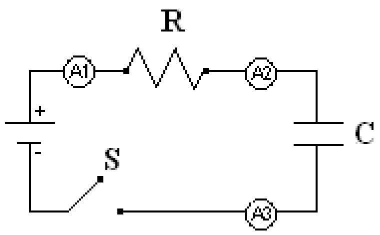

Figure 2

a. $i_1 = i_2 > i_3$
b. $i_1 > i_2 > i_3$
c. $i_1 = i_2 > (i_3 = 0)$
d. $i_1 = i_2 = i_3 = 0$
e. $i_1 = i_2 = i_3 \neq 0$

2. In the circuit of Figure 3, R is a resistor, C a capacitor initially discharged and S an open electric switch. When closing the switch, one can state that while the capacitor is being charged, the potential difference magnitude across R:

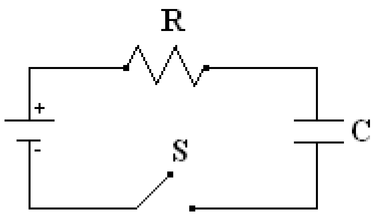

Figure 3

a. remains zero.
b. increases.
c. is the same as the one provided by the battery.
d. reduces.