“Real” experiments or computers in labs – opposites or synergies? : Experiences from a course in electric circuit theory

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“Real” experiments or computers in labs – opposites or synergies? 
Experiences from a course in electric circuit theory

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ABSTRACT

In this study we report from our experiences designing and re-designing a lab where engineering students studied transient response in electric circuits. In the first version of the lab students had difficulties doing the mathematical modeling of the experimentally measured graphs as it required students’ to link the time- and frequency domains as well as the object/event and theory/model worlds simultaneously. In the re-designed lab some computer simulations were included together with the original experiments on real circuits. The simulations opened up for learning and enabled students to establish links that are hard access directly with real experiments. Still doing real experiments is important to secure students ability to make links between models and theories and the physical reality. This study demonstrates that synergetic learning effects can be achieved by a careful design using an insightful combination of real experiments and computer simulations. Hence, we propose that the question of “real” experiments or “virtual” labs using computer simulations are best for students’ learning is not an either or question. Rather, it is a question of finding the right blend to achieve synergetic effects.

Conference Key Areas: Engineering education research, curriculum development, physics and engineering education

Keywords: Interaction analysis, experiential learning, modeling, simulations.

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INTRODUCTION

A common question in the context of lab instruction is if “computer simulations can replace real experiments”? However, the results from earlier research contrasting similar labs using real versus virtual environments have been contradictory. Some studies have reported better learning results with simulations, while other studies have reported that there is a risk that simulations become a world in itself and that students’ do not develop links between theories and models to objects and events in physical reality [1–4]. In this study our question was not about replacement, but instead if “real” experiments and computer modelling and simulations could supplement each other, i.e. if synergetic effects could be achieved (cf. reference [5]).

This paper is organized as follows: Section 1 describes the setting of the study, the object of learning and the purpose of the study; Section 2 describes the theoretical framework and the qualitative methodology used, i.e. design-based research, variation theory, interaction analysis, and the learning of a complex concept model; Section 3 presents the findings of the current study; finally, Section 4 presents some conclusions and a summary.

1 BACKGROUND AND SETTING

1.1 Setting

Students’ learning in an electric circuit theory course was studied. The electrical engineering students took this course during the whole spring semester in their first year of studies when this study was undertaken. The first part of the course covered standard DC- and AC-theory, while the second part of the course covered electric circuits with periodic, non-sinusoidal signals, using Fourier series and transfer functions and transient response using Laplace transforms. This study is part of a series of studies aiming at developing insightful learning in physics and electrical engineering through conceptual labs [5]. The focus in this study will be on students’ learning and understanding transient response in one of the labs. We have previously reported on the design of tasks using variation theory (see section 2.2) in this transient response lab [6]. In the present study a special emphasis will instead be on the question if simulations could be used to achieve additional learning effects.

1.2 Object of learning: Transient response

\[ x(t) \rightarrow \text{System} \rightarrow y(t) \]

\[ Y(s) = G(s) \cdot X(s) \]

\[ G(s) = \text{transfer function} \]

Fig. 1. a) A circuit viewed as a system where \( X(s) \) and \( Y(s) \) are the Laplace transforms of \( x(t) \) and \( y(t) \).

b) The electric circuit investigated in the transient response lab.

The input voltage is in this lab a step (practically achieved by a square wave with low frequency). \( L \) and \( C \) are kept constant and the value of \( R \) is varied. One of the explicit task posed in the lab instruction is to make a curve fit to the measured graphs of the current through the circuit for various values of \( R \). This basically comes down to find an appropriate mathematical expression to cause a calculated graph to give the
same curve as the measured graph, and to show both in the same figure. It was possible to do this in the same computer program – Data Studio – that was used to control the computer interface that generated the input voltage to the circuit and measured the current through the circuit and the output voltage.

The system in Fig. 1b is a second order and if the output signal $y(t)$ is taken as the current through the circuit the transfer function will be

$$G(s) = \frac{1}{L} \cdot \frac{s}{s^2 + \frac{R}{L} s + \frac{1}{LC}}$$

If the input signal $x(t)=u_{in}(t)$ is a voltage step applied at $t = 0$, depending on character of the roots of the denominator (poles) of $G(s)$ – i.e. if they are complex-conjugated, double real, or two real – the resulting current $i(t)$ will have the form

$$i(t) = \begin{cases} ae^{bt} \sin(ct) & \text{when } R < 2 \cdot \sqrt{L/C} \\ ate^{bt} & R = 2 \cdot \sqrt{L/C} \\ a(e^{bt} - e^{ct}) & R > 2 \cdot \sqrt{L/C} \end{cases}$$

The resistance $R$ is made up of a varying resistor resistance $R_{\text{res}}$ in addition to a resistance $R_{\text{coil}} \approx 6 \, \Omega$ from the inductor coil. Experimentally measured curves are displayed in Figure 2.

![Fig. 2. Experimental curves for a) the current and b) the capacitor voltage for different values of $R_{\text{res}}$ ($L=8.2 \, \text{mH}$ and $C=100 \, \mu\text{F}$) when the input voltage is a unit step.](image)

### 1.3 Purpose and research question

The original purpose was to design a lab to enhance students’ understanding of transient response in electric circuits and to study students’ learning process while doing the lab to evaluate the success of the design and any needs for improvements.

Students’ observed difficulties in the first version of the transient lab as is described below in section 3.1 led to the following revised research question: To investigate if a re-design of the transient response lab to include computer simulations, together with experiments on real circuits, could improve students’ learning? I.e. could links be made across the circle in Fig. 3a, and not only along the perimeter? The hypothesis was that the simulations could open up for learning and enabling the students to establish links that are hard access directly with real experiments.
2 THEORETICAL FRAMEWORK AND METHODOLOGY

2.1 Design-based-research

The empirical study described in this paper has been conducted within a series of projects [5] aiming at improving physics and engineering education that can be described as examples of design-based-research [7–9]. According to Lo et al. [10] the “benefits of design experiments are that we will be able to contribute to theory development, and improve practice at the same time”. It is thus “a systematic attempt to achieve an educational objective and learn from that attempt”. In a design study educational activities are investigated in cycles of design, enactment, analysis, and re-design where the development of educational designs goes hand in hand with the development of theories and methodologies. Using the methods of design science we present in reference [11] a more thorough description of this simultaneous development than can be described in this short paper.

2.2 Variation theory

A framework that was used in the design of the labs was variation theory [12, 13]. According to this theory, it is important to ensure that the learning environment enables students to focus on the object of learning and discern its critical features to promote effective learning. Central to variation theory is the notion that we discern certain aspects of an environment by experiencing variation, rather than by recognizing similarities. Important concepts are hence discernment, simultaneity, and variation. When one aspect of a phenomenon or an event varies, while one or more aspects remain the same, the aspect that changes is the one that will be discerned. One of the main themes of variation theory is that the pattern of variation inherent in the learning situation is fundamental to the development of certain capabilities. Experiencing variation amounts to experiencing different instances of the object of learning simultaneously. This simultaneity can be either diachronic (experiencing, at the same time, aspects of something that we have encountered at different points in time), or synchronic (experiencing different coexisting aspects of the same thing at the same time).

Marton related learning to what students could possibly experience in a particular classroom situation, stating that in a learning situation “the critical aspects that it is possible [for a student] to discern … make up the enacted object of learning” [13, p. 27]. Another important distinction in a learning situation is the difference between the intended object of learning (the knowledge, values, and skills the teacher or curriculum designer wants the students to learn) and the lived object of learning (the critical aspects that could be discerned and that the student actually discerns, i.e. what the student learns in the end).

2.3 Interaction analysis and learning of complex concepts

Analysis of the learning that occurs in the different versions of the transient lab was performed in several steps: First, to study students’ interactions [14] and their in situ development of their lived object of learning some lab-groups (each comprising 2-3 students) were recorded using a digital camcorder, obtaining a total of 80 h of video from the original and the re-designed versions of the transient response lab. This data was subsequently used to detect typical interaction patterns. We were particularly looking for what the students’ did during the labs, what resources they used, what they made relevant, and how they oriented themselves towards the object of learning. After repeated viewings, some episodes were found to contain more interesting and comparable activities. These episodes were originally transcribed to allow for detailed examination of interactional patterns.
The results of our analysis of the enacted and lived object of learning in the first version of the transient lab were, in line with the methods of design-based-research, used as an input and point of departure in the revision of the transient response lab.

As already mentioned (see section 2.1) one feature of design-based-research is the simultaneous development of educational practice and theories and methodologies. To represent students’ courses of action in complete lab-sessions we have further developed the notion of “practical epistemologies” [15, 16] into a graphical model - tentatively named the “learning of a complex concept” (LCC) model [17–19]. The LCC-model was suitable for our analysis as the transcription of analysis of transcripts from, labs lasting several hours is awkward and it is difficult to get a good overview. In this model “single concepts” are illustrated as nodes or “islands” that may be connected by links, while the links students actually make (identified by analysing the lived object of learning), or are supposed to establish (identified by analysing the intended object of learning), are represented by arrows. The nodes in our model are found by looking for “gaps” in the actions and conversations of students. A gap corresponds to a non-established link, and when a gap is filled and the students establish a relation between two nodes this is represented by an arrow indicating the direction of the link. The LCC-model also extends Tiberghien’s [20] model of object/event and theory/model ‘worlds’. In Fig. 3 and 4 entities analytically categorised as belonging object/event world are shaded and those categorised as belonging to the theory/model world are un-shaded.

The idea behind the LCC-model is that knowledge is holistic. The learning of the whole object of learning – the complex concept – is made through making explicit links. Thus the more links that are made, the more complete knowledge becomes.

3 RESULTS

3.1 Student learning in first version of transient lab

One of the intended objects of learning in transient lab is that students’ should understand that the characteristics of the poles of the transfer function \( G(s) \) determines the characteristics of the response (output signal). In this case, that varying values for the resistance will result in different types of responses.

![Graphical model](image)

**Fig. 3.** a) Enacted and lived object of learning in the first version of the transient lab. b) Students’ focus when making curve fits using mathematical functions to model the response in the time-domain in the first version of the lab.

Furthermore, the students were instructed to make a curve fit to the experimental curves for \( i(t) \) (see Fig. 2a) for varies values of \( R_{\text{res}} \) and from the curve fit determine the values for \( R \), \( L \), and \( C \) in the circuit (see Fig. 1b). This turned out to be a very difficult task for most students. This requires that the students identify what type of
function the different curves in Fig. 2a correspond to. However, although the students in practice only had two functions to choose from – either $ae^{bt}\sin(ct)$ or $a(e^{bt} - e^{ct})$ for $t > 0$ – they used all types of functions as an onset. Analysis of the videotapes recording students’ discourse in this first version of the lab, and observations, revealed that students during the lab mostly worked with one concept/entity (see Fig. 3a) at a time. Students avoided, or postponed, to do the necessary mathematics. It was commonly done after the lab-instructor had pointed out its necessity and only as late as possible. Students’ discussions were focused on the process and a typical question was “is this good enough for the report?”

A more detailed analysis revealed that, when making curve fits, students only focused on the measured graphs, the calculated graph from the curve fit, and the function used to make the curve fit (See Fig 3b). No links were made to the transfer function.

In the first version of the transient lab the task structure (i.e. the enacted object of learning) followed a circular path as displayed in Fig. 3a. Consequently students’ learning trajectory (i.e. lived object of learning) followed this pathway. As is discussed in section 3.1 students had difficulties to mathematically model the step response in an appropriate way and to draw conclusions from their model. Although the intended object of learning was that they should be able to make a link between the measured graphs this was not apparent in the task structure. Actually, as can be seen in Fig. 3 it was only possible for students to make links between the object/event and the theory/model world at two places.

3.2 Student learning in the re-designed version of the transient lab

Thus, the objective became to design tasks that would facilitate making links across the circle. By using, for example, Simulink® it is possible to simulate the step response to various transfer functions and get the results in a graphical form.

It was decided to include simulations using Simulink® in the revised lab. In line with Variation theory [12, 13] the transfer functions were systematically varied. For example, three forms for the denominator were used $(s^2 + 2s + 5, s^2 + 2s + 1, \text{and } s^2 + 2s + 0.75)$ with complex-conjugated roots, a double root, and two real roots respectively. In the initial trials, two numerators were used (5 and $3s + 5$) giving 6 combinations of numerator and denominator. In subsequent revisions, 3s was added as a third numerator.

![Fig. 4](image_url) a) Triangular routes enabled by the inclusion of simulations in the revised version of the lab. b) Students’ lived object of learning at the end of the revised lab.

Classroom observations and the video-recordings revealed that the students participating in the revised version of the lab worked in a rather different way. The
simulations enabled students to see where they were heading with the mathematics as the simulation outputs had similar forms as the experimental curves. However, it appeared that the mathematics felt easier for the students to start with as the transfer functions used in Simulink® had “nice numbers” (the denominator roots for the different transfer function were -1 ± 2j, -1, and -1 ± 0.5 respectively). Actually, in the original version of the lab completely analogous mathematics was involved in the modelling of the step response and measured graphs. However, as the numbers involved were not “nice”, it become a threshold for the students to overcome and in the first version of the lab students’ therefore dared not to start with the mathematics.

Our analysis is that the inclusion of simulations enabled the students’ to establish a triangular route between the measured graph, the calculated graph, and the transfer function and another triangular route between the calculated graph, the function in the time-domain, and the transfer function as is shown in figure 4a. As a result the students were not afraid of the mathematics and started with it from the beginning. Discussion centred on the underlying content of the lab. During the lab students noticed the relationships between different experimental graphs instead of looking only at one curve at a time. Throughout the lab they made links between the “single concepts” and at the end of the lab all the observed students had established the links displayed if Fig. 4b indicating a richer understanding.

4 SUMMARY AND ACKNOWLEDGMENTS

Variation theory, was indeed, applied also in the design of the first version of the transient lab. However, according to our analysis the students’ were not able to discern the critical features of the object of learning. The inclusion of the simulations enabled students to focus on the object of learning and discern its critical features.

The result of this study and other studies by us demonstrates that “real” experiments versus computer simulations may not be an either/or question. The study demonstrates that by careful design synergetic learning effects can be achieved by an insightful combination of real experiments and computer simulations. Simulations can, for example, reveal aspects that may be difficult visualize or achieve experimentally while doing real experiments secures students’ ability to make links between models and theories and the physical reality (i.e objects and events).

Furthermore this study, and other studies, points to the importance of the appropriate design of task structures in labs; i.e. the pedagogical design of a lab may be more important for learning outcomes than if it is “real” or “virtual” (cf. reference [21]).

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