Design-based educational research and development of engineering education: Examples from courses in mechanics and electrical engineering

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ABSTRACT

This study has been developed within a systematic framework to design innovative learning environments in science and engineering education. The aim of our research is to help students acquire a functional understanding of the subject matter. During for example labwork**,** students are expected to link observed data to either theoretical models, or to the "real world" they are exploring. However, according to a large body of research, establishing relevant connections between the concepts, the representations, the models and the observable objects and events is a very difficult task for students.

Our work was developed in line with the emergent methodology called “design experiments”, “design-based research” and “learning/lesson studies”, which is different from conventional approaches to designing innovative curricula. The benefits of design experiments are that we will not only test innovations in authentic educational settings, but also that we will be able to contribute to theory development at the same time. Our designs have utilised insightful and careful application of technical artefacts as mediating tools enabling, for example, simultaneous displays of many different modes of the concepts involved. In our paper we will give examples of theory developments: How our in-depth analysis of students’ performance have led to a model of "a complex concept" and to greater insights in how students try to establish relationships between the "worlds" of theories/models and of objects/events.

According our results, employing both quantitative and qualitative methods, our designs of courses in mechanics and in electrical engineering have been successful. We will relate central features of our designs to the theory of variation. Central in this theory is that we learn through the experience of difference, rather than the recognition of similarity. According to variation theory necessary conditions for learning are the experience of *discernment*, *simultaneity* and *variation*. We will also show how this theory have helped us, together with a method for analysis of students actions developed by us, to identify critical aspects for learning and thus have helped us to further improve our courses.

INTRODUCTION

An important aim of education should be to help students to acquire a "functional understanding" of the subject studied. Marton, Runesson and Tsui[1] have expressed this as follows:

> "Developing a learner's capability of handling novel situations in powerful ways, is considered to be one of the most important educational aims."

Similarly, Rorty[2] suggests that we should not

> "view knowledge as a matter of getting reality right, but as a matter of acquiring habits of action for coping with reality".

In accordance with this reasoning, we have previously argued that engineering students should learn not only to understand theories and models but also "to *apply* these models and theories"[3]. During lab work, students are expected to link observed data to either theoretical models, or to the 'real world' they are exploring. Tiberghien[4] proposed that the world of theories and models, and the world of objects and events can be seen as main categories in the analysis of knowledge. It is argued that this categorisation is very effective when analysing and developing learning environments, such as labs. According to recent research, students or novices have problems establishing relationships between the object/event world and the theory/model world. It is important to make explicit the links between the theory/model world and the object/event world in education. For example, Vince and Tiberghien[5] state that "establishing relevant relations between the physics model and the observable objects and events is a very difficult task" and at a physics education conference at Tufts University, the researchers present agreed on the following conclusion[6, 7] (see also work by Roth and Bowen[8, 9]):

> "Connections among concepts, formal representations, and the real world are often lacking after traditional instruction. *Students need repeated practice in interpreting physics formalism and relating it to the real world*" (emphasis in original).

Roth[8] found that students were "referentially stuck in the symbolic and associated conceptual representations, and experienced the phenomena as something unrelated".
At university level, the links students are supposed to make between the theory/model world and the object/event world are often links between mathematical models and measurement data, or graphs stemming from mathematical calculations and/or derived measurement data. This is often seen as the fundamental purpose of lab work[10]. Our research, and studies by other authors, have shown that these links do not occur spontaneously, even when the set task is to compare graphs stemming from calculations to graphs derived from measurements.

Although it is very important in our view to recognise the differences between science and engineering, and that engineering is not equivalent to applied science[11-24], engineering education research could learn much from, and be inspired by, science education research. The findings of research in physics education may be especially relevant because there is a substantial overlap in subject matter and because it has been more extensively investigated over a longer period than education in engineering (and probably other scientific disciplines).

Research in physics education may have the longest tradition. According to a large body of research in physics education it is difficult for students to acquire a functional understanding of canonical physics [6, 25-32]. This line of research has shown that students, even after studying physics at university level, hold conceptions (usually called misconceptions or alternative conceptions) very different (e.g. current is "used up" in a series circuit) from those held by experts (e.g. energy is "used up" so long as a current flows in a series circuit).

This “misconception” research have been criticized for solely describing “problems” in student understanding and failing to develop strategies that would help students to construct more sophisticated understandings.

However, an emergent approach in educational research, dubbed names such as ‘design-based research’, ‘design experiments’ or ‘learning studies’ aims to describe approaches that will facilitate learning. In this paper we provide some examples on the application of these approaches and implementation of insights from educational theory and philosophy of technology in the development of engineering education. The examples are chosen from the domains of mechanics and electric circuit theory, both of which are considered difficult to learn but encompass concepts that are important for an engineer to have a good functional understanding of. In our studies we have focused on developing educational approaches that are lab-based, which provides another reason for drawing on physics education research, in which there has been a long tradition (especially in the USA) of developing a range of ’active engagement curricula.

THEORETICAL BACKGROUND AND FRAMEWORK

Design-Based Educational Research

In the last ten years, several non-conventional approaches to designing innovative curricula have emerged. These approaches have been described, as noted above, as “design experiments”[33] or “design-based research”[34-36]. Cobb et al.[33] described this shift in these terms:

> “Prototypically, design experiments entail both ‘engineering’ particular forms of learning and systematically studying those forms of learning within the context defined by the means of supporting them. This designed context is subject to test and revision, and the successive iterations that result play a role similar to that of systematic variation in experiment”.

The Design-Based Research Collective[36] has described design-based research as having the following five features:

> “First, the central goals of designing learning environments and developing theories or ‘prototheories’ of learning are intertwined. Second, developments and research take place through continuous cycles of design, enactment, analysis, and redesign … Third, research on designs *must lead to sharable theories* that help communicate relevant implications to practitioners and other educational designers … Fourth, research must account for how designs function in *authentic settings*. It must not only document success or failure but also *focus on interactions* that refine our understanding of the learning issues involved. Fifth, the development of such accounts relies on methods that can document and *connect processes of enactment to outcomes of interest*.” (Our emphasis)

Lo et al.[37] have expressed one of the main features of this approach as:

> “The benefits of design experiments are that we will be able to contribute to theory development, and improve practice at the same time.”

Our study has several features similar to those described above, including focusing on interactions in an authentic setting. We demonstrate below ways in which we have implemented variation theory[38] in our design, and linked it to observed outcomes in students’ performance. In previous papers[39-41] we have discussed how our research has led to the notion of a ‘complex concept’ and the notion of ‘key concepts’[42] – thus our studies have developed sharable theories in addition to corroborating the value of variation theory.

Variation Theory

Variation theory, developed by Marton and co-workers[38, 43, 44], provides an explanatory framework describing the conditions required for learning. Central to this theory is that we learn through the experience of difference, rather than the recognition of similarity. To open up for learning should be understood in terms of *discernment*, *simultaneity* and *variation*. Learning is seen as developing certain capabilities and values that enable the learner to handle novel situations in powerful ways.

Powerful ways of acting emerge from powerful ways of seeing, and our previous experiences affect the way in which we experience a new situation. Our perception also affects the experiences we see as relevant, and the powerfulness of one's act is relative to one's aims in a given situation.

> "Thus it can be seen that people act not in relation to situations as such, but in relation to situations as they perceive, experience, and understand them. … If we want learners to develop certain capabilities, we must make it possible for them to develop a certain way of seeing or experiencing. Consequently, arranging for learning implies arranging for developing learners' ways of seeing or experiencing, i.e., developing the eyes through which the world is perceived."[1]

Seeing something in a particular way can be defined by the aspects discerned by a person at a certain point in time. The difference between 'discerning' and 'being told' should be noted. People discern certain aspects of their environment by experiencing variation. When one aspect of a phenomenon or an event varies, while another aspect or other aspects remain the same, the varying aspect 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. In the words of Marton, Runesson and Tsui[1]):

> "What we believe is that variation enables learners to experience the features that are critical for a particular learning as well as for the development of certain capabilities. In other words, these features must be experienced as dimensions of variation."

According to Marton, Runesson and Tsui[1] the following patterns of variation can be identified:

1. *Contrast*: As mentioned above, in order to experience something, a person must experience something else to compare it to.
2. *Generalisation*: However, in order to fully understand what "three" is, for instance, we must also experience varying appearances of "three",
3. *Separation*: In order to experience a certain aspect of something, and in order to separate this aspect from other aspects, it must vary, while other aspects remain invariant.
4. *Fusion*: If there are several critical aspects that the learner has to take into consideration at the same time, they must all be experienced simultaneously.

Experiencing variation amounts to experiencing different instances simultaneously. This simultaneity can be either *diachronic* (experiencing instances that we have encountered at different points in time, *at the same time*) or *synchronic* (experiencing different co-existing aspects of the same thing at the same time).

Marton, Runesson and Tsui[1] also introduce the concept of a learning space:

> "A *space of learning* comprises any number of dimensions of variation and denotes the aspects of a situation, or the phenomena embedded in that situation, that can be discerned due to the variation present in the situation. Variation that is not present in the situation can still be discerned, however, if variation is brought in by means of the learner's memory of previous experience. We should notice, here, that 'a space' does not refer to the absence of constraints, but to something actively constituted. *It delimits what can be possibly learned (in sense of discerning) in that particular situation. … The space of learning tells us what it is possible to learn in a certain situation [from the point of a particular object of learning]. … The space of learning ... is ... an experiential space. …*" (First emphasis in original.)

Marton and co-workers[1, 38, 45] distinguish between the *intended object of learning*, the *enacted object of learning* and the *lived object of learning*. The intended object of learning is the subject matter and the skills that the teacher or curriculum planner is expecting the students to learn. The enacted object of learning is the space of learning constituted in a learning environment, i.e. what is made possible for the student to learn. The lived object of learning is the way students see, understand, and make sense of the object of learning and the relevant capabilities they have. A further distinction is made between the *lived object of learning (1)* corresponding to the knowledge and capabilities students have when teaching starts and *lived object of learning (2)* corresponding to what students have actually learned when the teaching ends.

Linking and modelling

Students are expected to link observed data, especially during lab work, to either theoretical models, or to the real world they are exploring (see figure 1). Following Bunge[46], Tiberghien and co-workers[5, 47] have proposed that the world of theories and models, and the world of objects and events could be seen as main categories in the analysis of knowledge. It is argued that this categorization is very effective when analyzing and developing learning environments such as labs. According to recent research students or novices have problems establishing relations between the object/event world and the theory/model world. It has been suggested that it is important to make explicit the links between the theory/model world and the object/event world in education. For example, Vince and Tiberghien [5] state that

> "establishing relevant relations between the physics model and the observable objects and events is a very difficult task"

and at a physics education conference at Tufts University the researchers present agreed on the following conclusion[6, 7]:

> "Connections among concepts, formal representations, and the real world are often lacking after traditional instruction. *Students need repeated practice in interpreting physics formalism and relating it to the real world*" (emphasis in original).

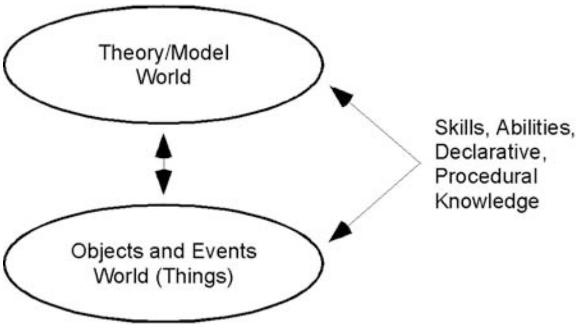


Figure 1. *Categorization of knowledge based on a modelling activity*[5].

Roth and Bowen[9] have investigated the interpretations of both professionals and students of the relationship between phenomena and their graphical representation. They conclude:

> "Our research shows that competent readings are related to understanding of both the phenomena signified and the structure of the signifying domain, familiarity with the conventions relating the two domains, and familiarity with the translating between the two domains. Graphs are not significant (signifying!) signs on their own. … Finally, only through the *continuous movement between the experiential and expressive domains* do we expect students to begin to dissociate the features of the two, which lead, without familiarity in translating, to iconic errors.

> To deal with all these issues will require much more than traditional instruction in graphing has allowed for. To read a graph competently, one needs more than instruction on the mechanical aspects of producing graphs. *One's extensive interaction with the phenomena and representational means seems to be prerequisite for competent graphing practises*." [Our emphasis]

Extending the work of Roth and Bowen cited above into the domain of electric circuit theory and generalizing their results, we have previously argued[48]:

> "Our analysis also suggests that the competent use of mathematical representations and competent translations and back forth between the experiential ('real' world observations) and expressive (mathematical representation, graphing, talking …) domains is very similar to that required in graphing as discussed by Roth and Bowen. … [We must] help students relate electric circuit phenomena to their representational means (mathematical and graphical). … [T]he results of our research and other researches support this claim, that this must expressively and extensively be cultivated to make the process transparent to students."

Based on previous work[48], we proposed the model displayed in figure 2 to illustrate the different processes involved in proceeding from the "real" world to a representation and in the opposite direction from a representation to the "real" world. The model was developed in the context of applying phasors (representations of circuit entities by complex numbers) and Laplace transforms. We also wanted to illustrate that mathematical manipulations and transformations are made within the world of models and claimed that too much focus in traditional teaching is on this and too little on "linking".

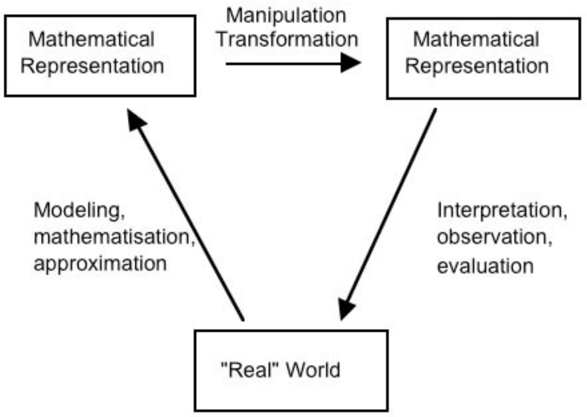


Figure 2*. Steps involved in modelling or the use of mathematics in, for example, problem solving*

These claims are in line with the following conclusion by Roth[8]:

> "These students were referentially stuck in the symbolic and associated conceptual representations, and experienced the phenomena as something unrelated. Kaput (1988) made the same claim for school mathematics. It is referentially stuck in the manipulation of symbolic notations and structures. There are no references to concrete events or the abstract entities describing these events." (p. 58)

To summarize the findings and claims presented above, all of them highlight the importance of making explicit the links between objects/events and the theory/model world.

The model of a complex concept

Research in science education has for a long time dealt with misconceptions of "single" concepts[49] and research is also often done is also often planned and performed within a mental model-based perspective[28]. We have previously argued that we need to investigate what are called *complex concepts*, i.e. concepts consisting of holistic systems of "single" interrelated concepts[39] (figure 4). In accordance with experientially based perspectives[50-53] we see conceptions as reflecting person – world relationships. Vygotsky[54] and Cole[55] have represented such a relationship by a mediational triangle (figure 3a), illustrating that there is no simple relationship between subject and object. Similarly, as shown in figure 3b there is a triadic relationship involving intentionality, rather than a dyadic mirroring relationship between a sign and the object represented. In accordance with these views we hold a non-dualistic world-view or, as stated by Dewey[50].

> "experience … is neither exclusive and isolated subject or object, matter or mind, nor yet one plus the other" (p. 384).

This non-dualistic and relational perspective is closely related to phenomenological and post-phenomenological traditions in the philosophy of technology[11, 13, 19, 56, 57].

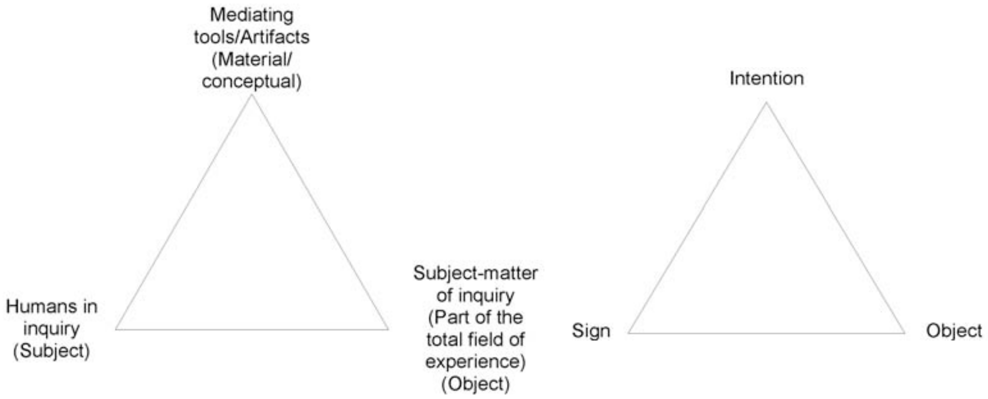


***Figure 3**. **a)** Model showing the concept of mediation adapted and modified from Vygotsky[54] and Cole[55]: The triadic relationship between subject – mediating tools – object. **b)** Peirce and Dewey's concept of representation as a triadic relationship.*

As pointed out above, Tiberghien and co-workers categorize knowledge between the object/event world and the theory/model world. They point out that the links between the theory/model world and the object/event world are important to make explicit in education.

The links students at university level are supposed to make between the theory/model world and the object/event world are usually links between mathematical models and measurement data, or graphs stemming from mathematical calculations and/or measurement data. Earlier research has shown (e.g. Tiberghien[47], Ryegård[58], Bernhard & Carstensen[48], Roth & Bowen[9]) that these links do not occur spontaneously.

Thus, it is important to make clear what these links consist of. In engineering education the concepts taught are mostly complex concepts, for which some links extend from one of the worlds to the other while others make connections within the same world. In order to identify these links and enable them to be highlighted in lab instructions, there is a need for an extended model that shows all links, and whether these links form connections within just one of the worlds or between them.

We therefore suggest a new model, which builds on Tiberghien's model and our earlier work, see figure 4 below. The different concepts taught are illustrated by "islands" that have different sizes according to the content of knowledge they represent. The arrows show the links between different concepts. The model may be used to analyze intended links, or links actually made by students (by identifying the "arrows", the islands between which arrows can be drawn, and the direction(s) of the arrows), depending on whether the research concerns analysis of "the intended object of learning" or "the lived object of learning" (Runesson & Marton[45]).

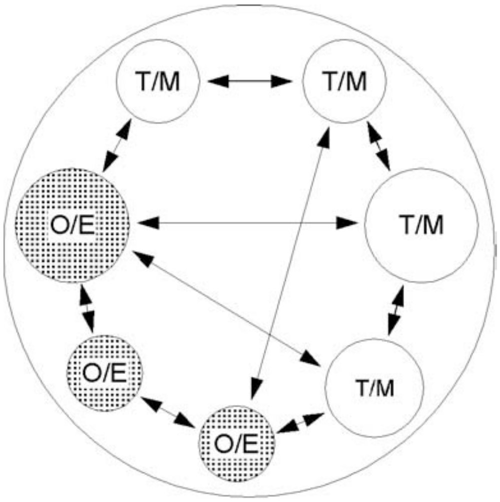


Figure 4*. Our suggested new model – Learning of a complex concept. T/M and O/E refer to relational concepts in the theory/model and object/event worlds, respectively.*

The rationale of our model is that knowledge is built both by learning about the pieces, the islands, and about the whole domain by making explicit links through simultaneous work upon the issues involved in several objects. Some links can apparently be made between specific parts or "islands", while others must apparently link all of the islands in the circle, presumably because they require understanding of the domain as a whole rather than just specific parts of it. We believe that the links may become established through interaction between different pieces of knowledge, through the interaction between the theory/model world and the object/event world. The more links that are made, the more complete the knowledge becomes.

In our studies we have found it important to identify the links that seem to provide the most knowledge, and those that seem to be most accessible to the students. Some of the links can be made between graphs stemming from mathematical expressions and graphs derived from measurements, which the novices experience as different representations while they seem to be identical to experts.

The method we used to identify aspects that were difficult for students to learn was to look for the questions raised during labwork, a method that provides different insights into what really is troublesome than commonly used recalled interviews, since the latter can only show what is remembered afterwards, which might not be the same. In particular, we argue that aspects taken for granted by teachers are highlighted by this approach.

Lab work

During labwork students are expected to link observed data to either theoretical models or to aspects of the real world they are exploring. In recent research some of the problems associated with this expectation have been examined, i.e. the failure of students or novices to perceive relationships between the object/event world and the theory/model world[10, 47, 59].

Tiberghien and her co-worker Vince[5, 47] provide a categorization of knowledge, as pertaining to the object/event world or the theory/model world, which has been shown to be very effective when analyzing and developing lab-instructions. They point out the importance of making explicit the links between the theory/model world and the object/event world in education (Figure 1).

Traditional taxonomy of laboratory instruction styles often suggests that there is a dichotomy between structured and open inquiry lab work. However, in our study we question this dichotomy and use our empirical data to show that students' courses of action in some dimensions are framed by encounters with the instructions, the technology, the teacher, and other peers, while in other dimensions they are free to explore. Lunetta[60] states that:

> "Laboratory classes have ranged from activities in which data are gathered to verify a stated principle or relationship to inductive activities, in which students seek to identify patterns or relationships in data which they gather. Teacher guidance and instructions have ranged from highly structured to open inquiry." (cf. Domin[61])

Arons[25] has summarised the problems associated with the different types of labs as follows:

> "It has long been clear that tightly structured and directed laboratory experiments are dull and demoralizing for the students and generate little in the way of concept development or physical understanding. It is also clear that the other extreme of completely unstructured situations, in which students are supposed to conduct their own observations, inquiry, and final syntheses are also ineffective."

Tight structuring and complete lack of structuring are not the only possible approaches to managing lab work, however. In recent decades there have been many attempts to create learning environments that are exploratory but also direct students' attention towards relevant concepts and phenomena, so-called *guided discovery*[62, 63] or *interactive-engagement labs*[64, 65]. Thus, the labs are inquiry driven, but the students are guided in their inquiry by carefully designed instructions, technology, and teacher support**.** Such attempts include curricular projects such as the Modelling Workshop Project[66] Socratic Dialogue Inducing Labs[67], RealTime Physics[68], and Tools for Scientific Thinking[69]. A common feature of the cited projects is that they make use of a certain technology called Microcomputer-Based Labs (MBL) or computerized data logging. MBL consists of a computer connected to a sensor or a probe and is used in the collection, analysis, and display of experimental data by transforming the sensor's signals to a graph on the computer screen.

However, we will claim that the labs described in this paper could be described as *highly structured open inquiry labs*, an implication of which is that we question some of the differences put forward in some taxonomies describing actual lab work. This has been discussed in more detail elsewhere[70, 71].

An important theoretical background concept for this study is that of tools in the socio-cultural theory of learning (e.g., Vygotsky[54], Cole[55], Kozulin[72], Säljö[73]). Much human interaction with the material and social world is not direct but mediated through the use of tools that could be expressed as: Human ⇔ Tools ⇔ World. These tools may be of various types such as "psychological tools" or artifacts and they affect the way we perceive and interact within our life-world. It has also been pointed out that we "think through technology" in some schools of the philosophy of technology (e.g., Ihde[74], Mitcham[11]), as discussed (*inter alia*) in previous papers on the philosophy of technology and education[75, 76].

The so-called Microcomputer Based Laboratory (MBL) is an example of the use of "inter-active technology" as a tool in physics education[77]. MBL was introduced into physics teaching almost three decades ago. In MBL activities students perform experiments using different sensors (e.g., force, motion, temperature, light and sound sensors) connected to a computer via an interface. The arrangement creates a powerful system for the *simultaneous* collection, analysis and display of experimental data, which is sometimes referred to as *real-time* graphing. This setting allows the development of labs that can effectively foster functional understanding of physics[7, 64, 78, 79-81].

METHODOLOGY

In this paper (based on a study that is part of a wider research programme), we analyse and describe the development of lab components of introductory mechanics and electric circuit theory courses for engineering students.' Learning is to experience the world in new ways[43]. To analyse learning is to analyse new ways of enabling students to experience their world. One way to do this is to observe students' behaviour (conversation and actions)[82] during lab sessions.

This, we claim, provides grounds for further explorations of the educational conditions for meaningful learning with interactive technologies in different types of learning environments and has raised interest in the following, interrelated questions:

How *do* the students approach the learning environment?

What aspects of the learning environment direct the students toward the intended object of learning and, in particular, how *do* students establish links between the real/event world and the theory/model world?

How can we further develop these aspects?

In the analysis of the labs in the electric circuit theory course we have applied the model of learning a complex concept described above. The different relational concepts are illustrated by "islands" (see figure 4), and arrows show the links between the different concepts. This model can be used to analyse the intended links, or the links actually made by students, depending on whether "the intended object of learning" or "the lived object of learning" is investigated. We have identified the items in our model by analyzing the questions the students raise during lab work[83]. Our methodology is a further development of Wickman's practical epistemologies[84], based on work by Wittgenstein[85].

The rationale underlying our model is that knowledge is built both by learning about component concepts (the islands) of a domain, and the whole domain, by making explicit links between the components. As mentioned above, some links can apparently be made between specific concepts, while others must apparently link all of the concepts because they require understanding of the domain as a whole. We believe that the links may become established through interactions between different pieces of knowledge. The more links that are made, the more complete the knowledge becomes (cf. Roth[8]). According to Tiberghien[86], the most difficult links to make are those that go between the two "worlds", therefore to identify those links and to explore possibilities for learning, one must identify the "problems" as well as the "potentials" (for similar results see Bernhard & Carstensen[48]).

To study student learning *in situ*, using our model, we videotaped and transcribed students' conversations and other actions in several Transient Response lab sessions. In each lab session we followed two groups (each comprising 2-3 students) with a video camera, and took a total of 56 h of video for study. In this paper we have included the results of this analysis, but not the transcripts (for which see other work by us[87, 88]). By this method it has been possible for us to follow the dynamics of students' learning and to do an in-depth study of critical aspects for learning in this specific context.

If we had decided to use questionnaires instead of our method of videotaping and analysing students' courses of action it had not been possible for us to investigate and discover *critical aspects* for learning transient response in electric circuit theory.
Using this method it was possible for us to follow the dynamics of students' learning in detail, and to identify and study critical aspects for learning about and understanding transient responses in electric circuits, which we would not have been able to discern if we had used

questionnaires and interviews, as done for instance by Entwistle and co-workers[89, 90]. The cited authors investigated teaching-learning environments and student learning in electronic engineering using questionnaires and interviews with selected students. The responses were therefore based on students' reflected understanding, post-course, of their learning experience (in contrast to our method, which enables aspects that the students may not be aware of, to be identified and investigated). Based on an analysis of the self-reports Entwistle and co-workers claimed that some of the main difficulties for students in learning analogue electronics were mathematical. However, our studies of students' courses of action and analysis of critical aspects during the course indicate, as will be discussed in more detail below, that students' difficulties lie not so much in the handling of mathematics as in linking between the theory/model world and the object/event world (and we obtained similar results in an earlier work in which we analysed learning about AC electricity[48]). Thus, using our method we believe we have obtained a more subtle understanding (*inter alia*) of the role of mathematics and critical aspects of the learning environment than we could have acquired using a questionnaire.'

In the mechanics part of this study we have used the research based conceptual test *Force and Motion Conceptual Evaluation (FMCE)*[91] to investigate the functional understanding in mechanics achieved by the students. The test uses multiple-choice questions to assess student conceptual understanding of mechanics. The distractors (wrong answers) are carefully chosen and correspond to common sense beliefs (misconceptions) as shown in the research literature on misconceptions. The multiple-choice format of FMCE makes it feasible to do controlled large-scale educational studies. The FMCE have been shown by their developers to be reliable and valid measures of student conceptual understanding of basic Newtonian mechanics [91]. Students response to the questions of FMCE in an open ended format correlates very well to their answers on the multiple-choice format. The FMCE-test was given to the students on one of the first lectures as a pre-test (one lecture, 45 min, were set aside for this) and after the course was finished the test were administered as a post-test.

LEARNING ENVIRONMENTS STUDIED

Mechanics

Developing a functional understanding of mechanics, in accordance with canonical physics, has proven to be one of the most difficult challenges faced by students. Studies by many researchers have shown that the misleading conceptions about the nature of force and motion, which many students have, are extremely difficult to change. These strong beliefs and intuitions about common physical phenomena are constituted by previous personal experiences and affect students' interpretations of the material presented in mechanics courses and later courses. Research has shown that traditional instruction does very little to influence students' "common-sense" beliefs (see for example McDermott[6] and references therein, Hake[64], Hestenes *et al*[92], McDermott & Redish[26] and references therein).

Most discussion on students' learning problems in mechanics has been written within a constructivist framework and very few successful attempts to design learning environments that foster conceptual understanding of mechanics have been reported in the literature.

However RealTime Physics[7, 91, 93], Tools for Scientific Thinking[94, 95] and Workshop Physics[96] are exceptions for which remarkable learning results have been reported.

The approach used in our development of labs using MBL-tools was inspired by, but not identical to, the pedagogical approaches applied in RealTime Physics and Tools for Scientific Thinking, and inspired by research in Physics Education (see, for example, McDermott[6], Thornton[7] and Laws[97]). In this paper we will not present a detailed analysis of the differences between our curricula and those mentioned above. Instead, we will focus on an analysis of the tasks, as expressed in the lab-instructions, in terms of *discernment*, *simultaneity* and *variation*.

> **Example 1**: *Acceleration with zero velocity*. In this activity students monitor the motion of a cart propelled by a fan (see figure 5) that provides an almost constant "visible" force and, hence, almost constant acceleration. In this task the students should give the cart an initial push in the direction opposite to the direction of the force, such that the cart will slow down and reverse its direction of motion (after studying the motion of the cart without reversing direction, with different directions of the acceleration). Students are first asked to observe the motion of the cart (without measuring it) and then to sketch predictions of how the motion will be represented by position-time, velocity-time and acceleration-time graphs. After they have made their predictions the motion of the cart is once more observed and this time the MBL-equipment is used to measure the motion, and simultaneously display it in a graph (a typical graph is shown in figure 6). To make accurate predictions not only do the differences between position, velocity and acceleration have to be discerned, but also the relationships between these concepts. Velocity and position vary, but students have to discern that the acceleration is constant and also that a zero velocity does not imply that the acceleration is zero. Asking the students to make predictions before the experiment is performed and comparing the outcome with their predictions facilitates comparisons of their thinking and the experimental graphs. If there is any discrepancy we could regard this as a variation in the space of thinking models. Students thus have the possibility to discern between different "models" and see which is the most powerful.

> **Example 2:** *Motion with friction*. Traditionally in physics courses friction is minimised in apparatus used to demonstrate the "validity" of the laws of motion (as manifested by the invention of the air track as a teaching tool). However, in this experiment friction is deliberately introduced and varied, by a special attachment to the cart, in order to introduce the frictionless "world" as a model and "limiting case". By varying the friction students encounter both of the cases $v \propto F_{\text{external}}$ and $a \propto F_{\text{external}}$. Variation is thus brought about in different thought models illustrating how friction can be accounted for within a Newtonian framework.

We are interested in all aspects of the learning environment that could help direct students' attention to important aspects of activities and foster understanding of specific concepts and the links between them. The students' participation in the lab is seen as being dependent on habits (i.e. previous participation), and possible to reframe through particular encounters. We have to distinguish between the intended object of learning, enacted object of learning, and students' lived objects of learning (1) and (2) (i.e. knowledge and skills before and after instruction). Central aspects of experimental graphs must be focused on in order to complete the assignments, and the students have to make certain conceptual distinctions.

The lab instructions developed specify the process and both the variance and invariance in the learning space according to the theory of variation. The questions are open-ended, but at the same time framed in such a way that to successfully complete tasks students have to deal with certain concepts in certain ways. In both the text box above and the appendix a brief example is given of the ways in which systematic variation is introduced in labs designed in line with suggestions from Marton's theory of variation and Tiberghien's work.

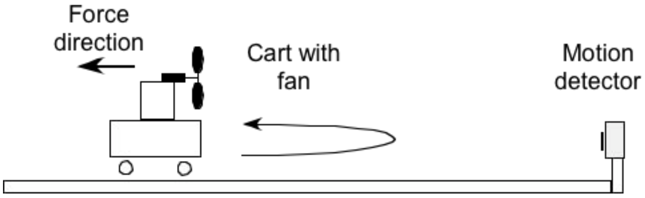


***Figure 5**. A typical setup in an MBL-experiment. A low-friction cart is pushed towards a motion sensor. A fan unit attached to the cart provides an approximately constant force in a direction opposite to the initial movement and thus the cart's direction of motion changes. The results are shown in figure 6. Note that the fan unit provides a visible source of the force.*

Other important factors in the learning environment are the scaffolding from teachers, which helps to elicit student knowledge and assists students to highlight central aspects of the activity, by directing their attention to key parts of the graph/activity while downgrading less important aspects. For for both teachers and education researchers, it is important it is important to understand what the students focus on and how they frame the activity.

The MBL-Technology gives immediate feedback through graphical representation. In the process of making the graph, the students can literarily see when they make mistakes. Multiple representations and resources are used. The students intertwine different interpretative resources as well as different experiential domains, such as graphical shapes, with narrative accounts of past actions

The students maintain a common orientation toward the graph through discussions with their peers, different interpretations are negotiated by the students and, thus, arguments become important elements of the process of solving the task.

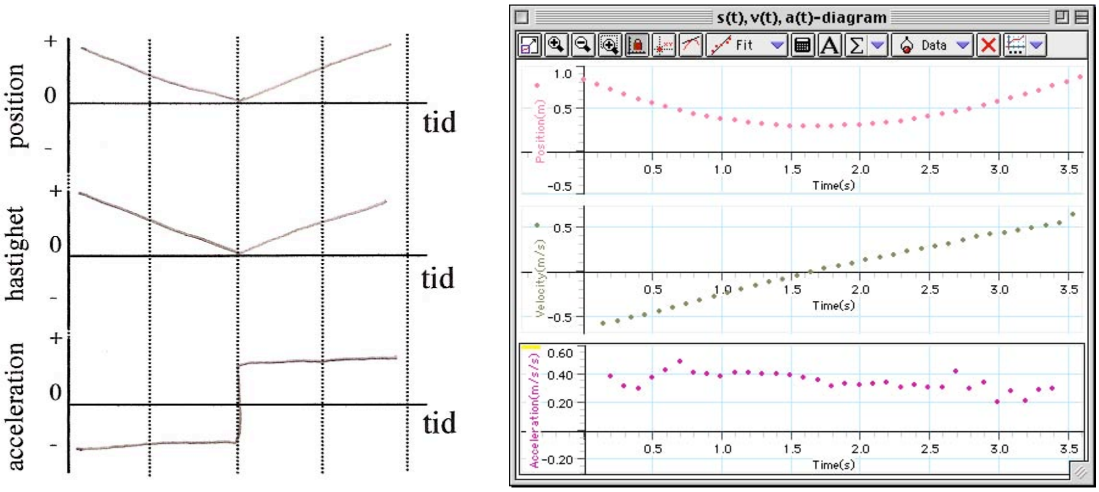


***Figure 6**. **a)** A prediction from a student regarding the motion described in the text and in figure 5 (Translation: hastighet = velocity, tid = time). This student's conception of motion is not according to canonical physics. **b)** Experimental results showing, in this case, a discrepancy between student prediction and the actual results.*

In figure 7 data from FMCE tests are shown, comparing results obtained before and after a mechanics course with "traditional" lab sessions (Mechanics I 97/98) and reformulated versions of the course with two variants of lab sessions in which MBL was used (MBL 02/03 and Richards-lab 02/03). It should be noted that the only difference between the MBL 02/03 and Richards-lab 02/03 courses were in the lab activities and instructions.

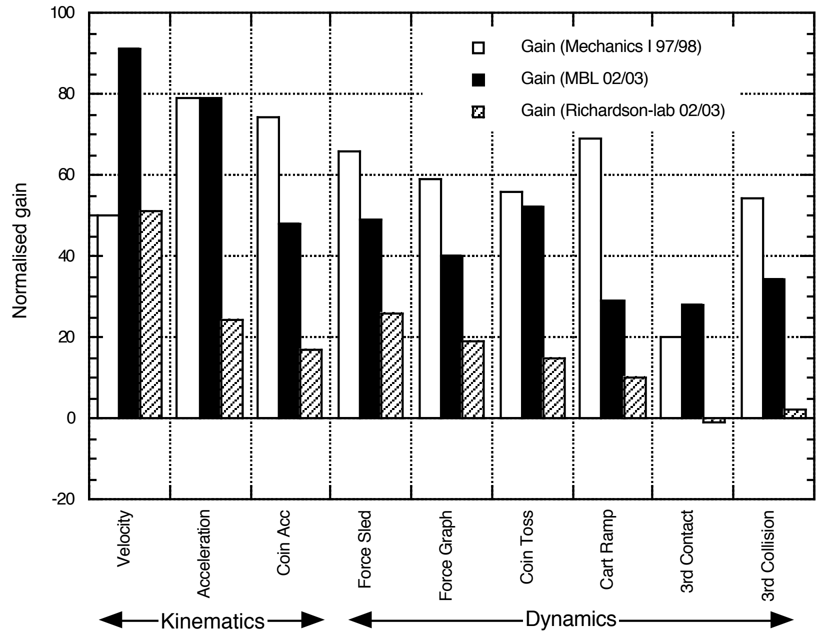


***Figure** 7. Normalised gains in different conceptual domains of mechanics as measured by the FMCE-test for different courses.*

Electric circuit theory

Most research on students' understanding of electric circuits has been in the domain of pre-university students' understanding of DC-circuits. According to this body of research[48, 98-107] students tend to confuse concepts such as voltage, current, power and energy. This means that students do not clearly distinguish between these concepts, and typical confusions follow from not relating them properly, such as:

Current consumption.
Batteries as constant current supplies.
No current – no voltage.
Voltage is a part or a property of current.

Research has also shown that it is very difficult for students to see a circuit as a system and to understand that local changes in a circuit result in global changes that affect all of the voltages and currents in a circuit. One can see both:

Local reasoning. Students tend to focus their attention upon a single point in the circuit. A change in the circuit is thought of as only affecting the current and/or voltages in the circuit where the change is made.

Sequential reasoning. If something is changed in the circuit it is thought of as only affecting the current and/or voltages in elements "beyond" the place where the change was made, not before it.

These phenomena were further investigated by Margarita Holmberg[14], as part of her thesis. She used a questionnaire to investigate the understanding of engineering students, in three different countries, of several concepts pertaining to electrical circuit theory. Her results from studying engineering students are similar to results previously obtained in studies of pre-university students. In particular, she typically found inconsistencies in student reasoning in cases of extreme values (zero or infinite) for voltage, current or resistance.

We will argue that the reason for these results is that students see concepts as isolated "things" and not as interdependent relations.

The project discussed in this section focused on a second semester course in electric circuit theory for first-year students studying electrical engineering at a Swedish university. The course included theory of DC- and AC-circuits, transients and frequency responses, periodic and semi-periodic signals, and the application of both transform (Phasor, Laplace and Fourier) methods and Fourier-series for solving circuit problems. *Electric Circuits* by Nilsson and Riedel[108] was the recommended textbook for the course at the time of our study.

In the first implementations of the reformulated course, in 2001 and 2002, new labs were introduced, that were developed by taking experience from developing conceptual labs in physics into account[78, 80, 109, 110]; the rest of the course (lectures and problem-solving sessions) remained traditional in format and structure. Our aim was to provide experiences[50, 111] that would encourage students to relate electric circuit phenomena to their representational means (mathematical and graphical).

Although in our study the new labs allowed the development of a functional understanding of the concepts involved in the course, our analysis showed that further improvements could be made. In 2003 we redesigned the logistics of the course; the problem-solving sessions were integrated into the labs and all lab instructions were rewritten. Problems similar to those found in textbooks were integrated into the instructions. However, the 'traditional' problems were not copied from the textbooks, but were carefully reworked in accordance with the theory of variation presented above. Ample consideration was given to how these problems could fit into a learning environment and foster an understanding of electricity as integrated holistic knowledge. One of the advantages of this integrated environment was that several tools were made available to the students during problem-solving: besides paper and pencils, students had access to mathematical tools such as MATLAB™, toolboxes such as SIMULINK™, circuit simulation software such as PSpice, and the opportunity to measure variables of real circuits. The labs were designed in such a way that the students were required to use several 'tools' to understand and handle the subject matter, including paper and pencil calculations, use of MATLAB™ or an associated toolbox, simulations, measurements of real circuits, and analysis of graphs.

In this paper we investigate students' behaviour in the Transient Response labs (2×4h), which are carried out late in the course.

The intended object of learning in these lab sessions was for students to develop a functional understanding, and obtain some experience of, transient phenomena in electric circuits. Students were also expected to develop an ability to use different tools, such as the Laplace transform, to analyse and explain these phenomena.

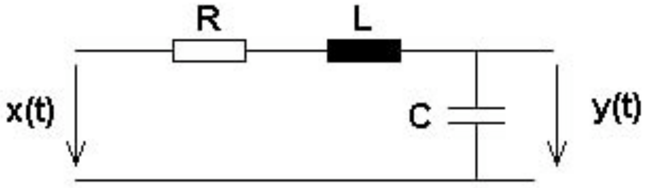


***Figure 8**. The circuit analysed in the transient response lab.*

The circuit analysed in this lab is shown in figure 8. For most tasks L = 8.2 mH and C = 100 μF, which was kept constant, while R was varied. The coil had a resistance of approximately 6 Ω and the external resistors ($R_{Resistor}$) were varied at 0, 10, 33 and 100 Ω, thus the total resistance (R) of the circuit was 6, 16, 39 and 106 Ω. The input voltage x(t) was a step-function achieved through a square wave with a long period-time and amplitude of 1 V.

The equation for the relationship between $v_{in}(t)$ and the current through the circuit can be written as:

$$x(t) = v_{in}(t) = R \cdot i(t) + L\frac{d}{dt}i(t) + \frac{1}{C}\int_{-\infty}^{t} i(t)dt$$

In our example, $v_{in}(t)$ will be given as a step-function where i(t) is sought. For most students such an integral-differential equation is difficult to solve. However, using Laplace transforms, this equation in the time-domain can be transformed to an algebraic equation in the frequency domain. Using $V_{in}(s) = 1/s$ for the voltage step and following standard procedures, it can be written as:

$$V_{in}(s) = R \cdot I(s) + sL \cdot I(s) + \frac{1}{sC} \cdot I(s) \Rightarrow$$

$$I(s) = \frac{V_{in}(s)}{R + sL + \frac{1}{sC}} = \frac{1/s}{R + sL + \frac{1}{sC}} = \frac{1}{s^2L + sR + \frac{1}{C}} = \frac{1}{L} \cdot \frac{1}{s^2 + s\frac{R}{L} + \frac{1}{LC}}$$

Depending on the relationship between R, L and C, the roots of the denominator $s^2 + sR/L + 1/(LC)$ will be complex-conjugated, a double or two real roots. Depending on the type of roots, we will obtain different types of functions corresponding to i(t). The types of functions corresponding to different R-values are presented in table 1.

R (Ω)	Roots of $s^2 + s\frac{R}{L} + \frac{1}{LC}$		Function
6	-366+1042j	-366-1042j	$ae^{-366t}\sin(1042t)$
16	-976+517j	-976-517j	$be^{-976t}\sin(517t)$
39	-272	-4484	$c(e^{-272t} - e^{-4484t})$
106	-95	-12832	$d(e^{-95t} - e^{-12832t})$

***Table 1**. Roots of the denominator $s^2 + sR/L + 1/(LC)$ and the corresponding functions for L = 8.2 mH and C = 100 μF.*

Here, it is possible to proceed from the *Real circuit → Differential equation → Laplace transform → Inverse transform → Calculated graph*. Finally, it is possible to compare the calculated graph with a measured graph.

It is also possible to proceed in the other direction: Measured graph as data points → Function fit to measured graph → Laplace transform → Real circuit.

For example, a fit to measured data in the form of:

$$i(t) = ae^{-bt}\sin\omega t \Rightarrow I(s) = a\frac{\omega}{(s+b)^2 + \omega^2}$$

can be compared to:

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

in order to give R, L and C *experimentally* from the curve-fit.

It is mentioned above that the intended object of learning in the Transient Response lab can be illustrated in the form of the *model for learning a complex concept,* as shown in figure 4. It is easy to identify the links mentioned above. These links are shown for the first and second tasks in figure 9a and 9b, respectively. The links that associate *Real circuit → Differential equation → Laplace transform* in figure 9b represent the links students are supposed to establish in order to make the reverse link: *Laplace transform → Real circuit*.

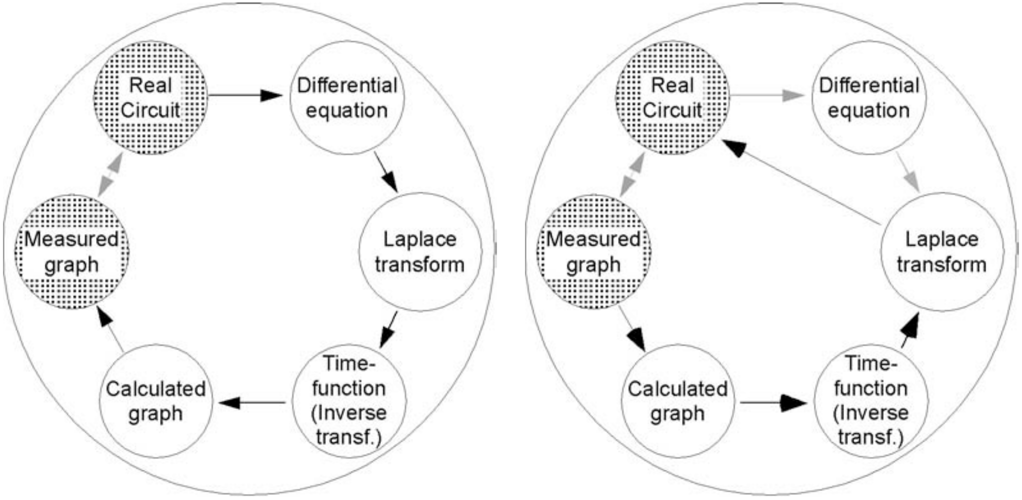


***Figure 9**. Analysis of different tasks (intended object of learning) in the lab-instructions (see text) in the light of our model (see figure 4) of the learning of a complex concept.*

In the first implementation of the Transient Response lab the students had one 4 h lab on transients and three 2 h sessions on problem-solving.

The task was to measure the current as a function of time through the RLC-series circuit (described in the section above) for different values of R. Students were also requested to measure the voltage over the capacitor in the circuit. Figure 10 shows typical results for the RLC-circuit with the coil's own resistance (approximately 6 **Ω**) as the only resistance; the experimental i(t) corresponds to a damped sine wave in this case.

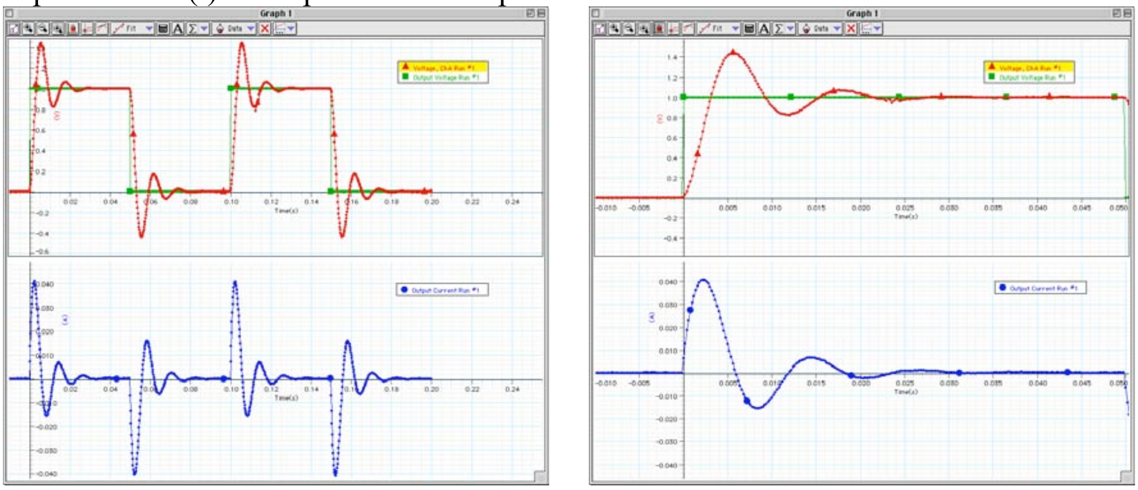


***Figure 10**. Results from measurements of current through the circuit (lower part) and voltage (upper part) across the whole circuit, and across the capacitor, for R = R_{coil}, L = 8.2 mH and 100 µF. The x axes of the graphs to the right and left have different time scales.*

The experimental results for i(t) for all the different values of R are shown in figure 11. Two qualitatively different graphs are shown that represent possible expected outcomes from that kind of input. Depending on the value of the resistor, the graph will show one or the other of the two different curves. The equations that will render the two different types of curves (see section B above) are either of type

$i(t) = ae^{bt} \sin(ct + d)$

or

$i(t) = ae^{bt} + ce^{dt}$

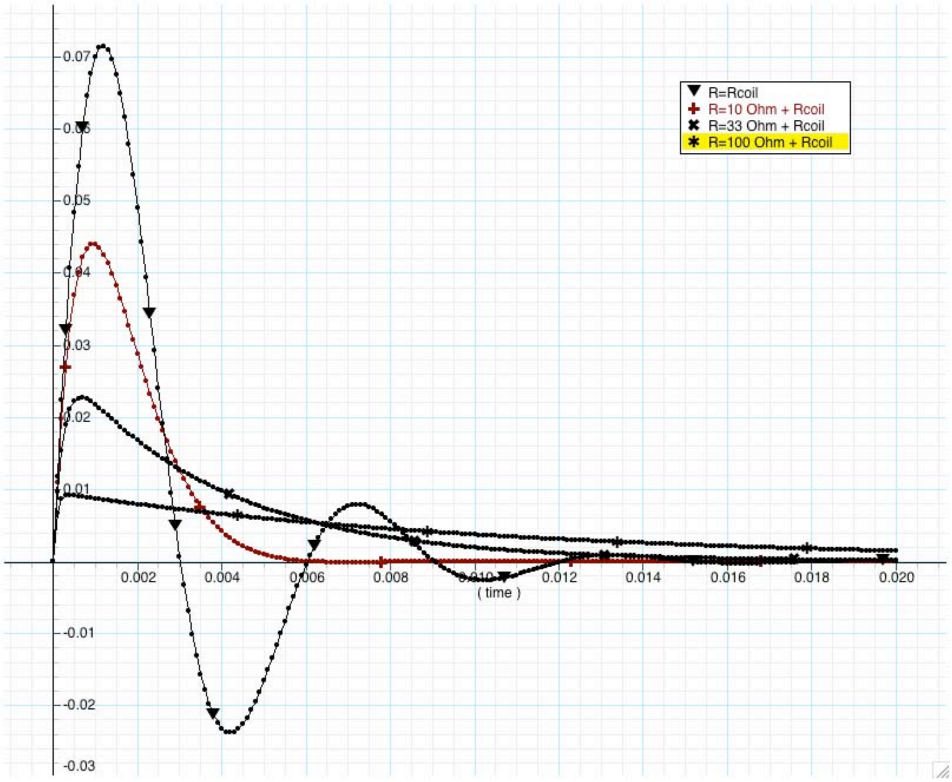


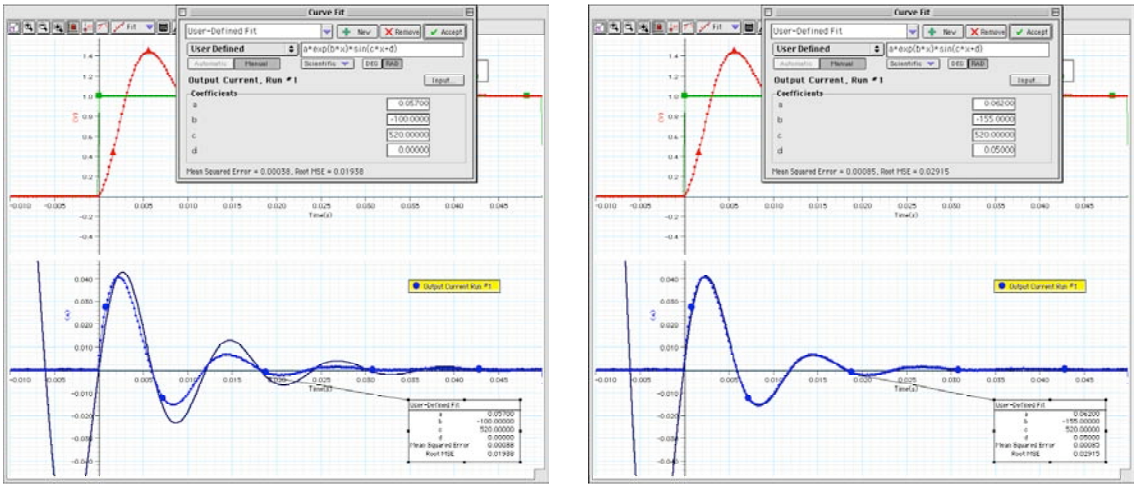
***Figure 11**. Typical experimental results for the current through the RLC-circuit with different resistor values.*

Only one of these equations was given in the lab instructions, since one aim was to make the students aware of the different solutions to the differential equations in the context of electric circuits. This should not have been too problematic for the students, who had attended previous problem-solving sessions, as part of their course, in which both of these equations were discussed. In the MBL-environment it is possible to display both the measured and the calculated graph in the same diagram, so one task was to enter ‘the right formula’ and change the parameters a, b, c and d, until the calculated and measured curves coincided. In figure 12, an example is shown of how a user-defined fit is made with the software used. Since we intended the students to acquire a ‘feeling’ for what the different parameters do, they were asked to fit a curve manually and select the most appropriate function.

The lab instructions asked students to fit curves to all four measured curves for i(t). Furthermore, they were required to calculate the corresponding R, L, C-values from the fitted curves. We expected them to notice and explain the differences between the different experimental curves and relate them to the theory.

In the design we expected that the variation in qualitatively-different types of experimental curves experienced in the lab, corresponding to qualitatively different types of roots (poles), would help to enhance the students’ understanding of transients and the application of Laplace transforms in electric circuit theory.

However, when we analysed the students’ courses of action in the first implementation of the course, we noted that there was a great deal of surface discussion and several ‘lingering gaps’[84]. No students from any group noticed that they should have used two different formulae for the curve-fitting and tried to fit a damped sine wave to the $R_{resistor} = 33$ and 100 Ω curves. It was still very difficult for students to make links between the theory/model world and the object/event world, despite the design being deliberately aimed to facilitate this linkage.



User Defined: a*exp(b*x)*sin(c*x+d)
Output Current, Run #1
Coefficients
a 0.05700
b -100.0000
c 520.00000
d 0.00000
Mean Squared Error = 0.00038, Root MSE = 0.01938

User Defined: a*exp(b*x)*sin(c*x+d)
Output Current, Run #1
Coefficients
a 0.06200
b -155.0000
c 520.00000
d 0.05000
Mean Squared Error = 0.00085, Root MSE = 0.02915

***Figure 12**. User-defined fit to experimental data. The left graph shows an unfinished fit and the right graph a fit that agrees well with the experimental data.*

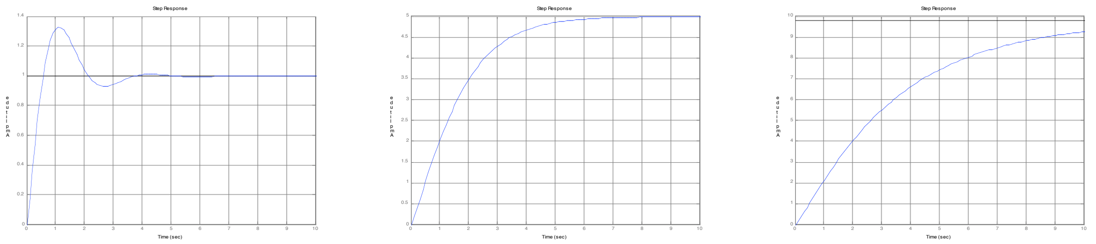
The overall objective of integrating problem-solving sessions and labs was to further widen the students’ opportunity to experience the links between the world of object and events and the world of theory and models. In the first implementation, the Transient Response lab lasted for four hours and the classroom sessions devoted to solving transient response and Laplace problems comprised three two-hour sessions; a total of 10 hours. In the second implementation this was changed to two four-hour sessions; a total of 8 hours.
The main difference in the second implementation of the transient lab was that the lab started with the six different Laplace transforms displayed in figure 13. Students were first asked to solve the problems using paper and pencil, then to simulate them with SIMULINK™.

In figure 13 the three different denominator polynomials correspond to three qualitatively different types of solutions. The resulting time functions g(t) are also shown in the figure. Besides experiencing the variation, due to the different characteristics of the roots of the characteristic polynomials, i.e. different types of poles, variation is also experienced according to the initial and final value theorems, as explained in points 2 and 3.

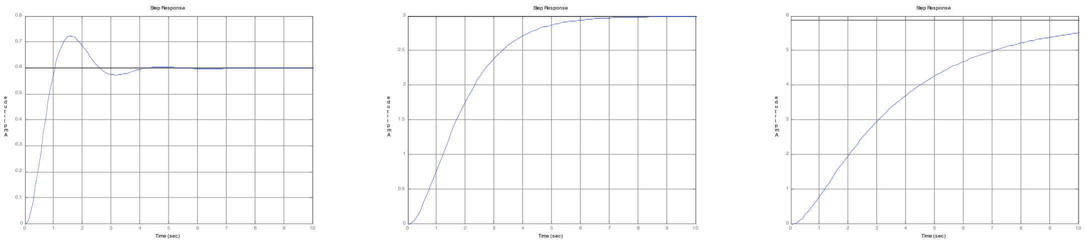
Typical ‘end of chapter’ conclusions in most textbooks are not systematically varied, as seen in Figure 13. In the first implementation these traditional textbook problems were used, but by using SIMULINK™ the characteristics of the different functions were visualised.

The next step in the instructions required students to work out the relationship $G(s) = Y(s)/X(s) = V_C(s)/V_{in}(s)$ with paper and pencil from figure 8. Students were then asked to inverse transform this relationship and calculate $V_C(t) = y(t)$ for some of the values of R, L and C that occur in the RLC-circuit. After this step students were asked to begin taking measurements of the transient responses of the real circuit. The task, the intended object of learning, in this part of the lab was very similar to that in the first version of the transient lab. However, the likeness in instruction in this part of the lab, the students’ course of action, and the lived object of learning, were very different in the two versions of the lab.

a) $G(s)=\dfrac{2s+5}{s^2+2s+5}$ b) $G(s)=\dfrac{2s+5}{s^2+2s+1}$ c) $G(s)=\dfrac{2s+5}{s^2+2s+0.51}$



d) $G(s)=\dfrac{3}{s^2+2s+5}$ e) $G(s)=\dfrac{3}{s^2+2s+1}$ f) $G(s)=\dfrac{3}{s^2+2s+0.51}$



Important characteristics:

1) Solutions to the characteristic polynomial, i.e. the poles to the transfer function give different shapes to the curves:

$$s=-1\pm\sqrt{1-5}$$
$$s_1=-1+2j$$
$$s_2=-1-2j$$

$$s=-1\pm\sqrt{1-1}$$
$$s_{1,2}=-1$$

$$s=-1\pm\sqrt{1-0.51}$$
$$s_1=-1+0.7=-0.3$$
$$s_2=-1-0.7=-1.7$$

gives under-critically damped behavior

gives critically damped behavior

gives over-critically damped behavior

2) Note the different start behaviour that depends on the difference in degree of powers in the numerator and denominator polynomials.

3) The Steady-State value depends on the transfer-function’s limit-value when s approaches zero.

Final value theorem $\lim_{t\to\infty} g(t)=\lim_{s\to 0} G(s)$

***Figure 13**. Examples of systematically-varied Laplace functions for the students to analyse, mathematically and graphically, in the Transient Response lab.*

To see how our analysis of learning was done, please refer to figure 14a-c. After the first part of the lab, the lived object of learning for the two students, Benny and Tess, could be described with the arrows displayed in the figure (left and middle circles, respectively). During our analysis we studied transcripts and video tapes from the lab. Benny and Tess were making different links and not communicating clearly. In the transcripts obtained from the later parts of the lab, Benny and Tess eventually engaged in mutual communication. From the analysis, it is also obvious that the students had difficulties connecting the mathematical representation to the measured graphs and the circuit they used. Tess and Benny displayed different lived objects of learning, and in order to fill the gaps they had to make links back to what they already knew. At this point, neither student was thinking about the real circuit, because in order to do so they had to make links back – Benny from the graph and Tess from the mathematics. At the end of the lab session Tess and Benny had made all the links described in figure 14c. Their discussion simultaneously covered two or more of the links, and their awareness of the other links were figurative, so they drew their conclusions from what they saw.

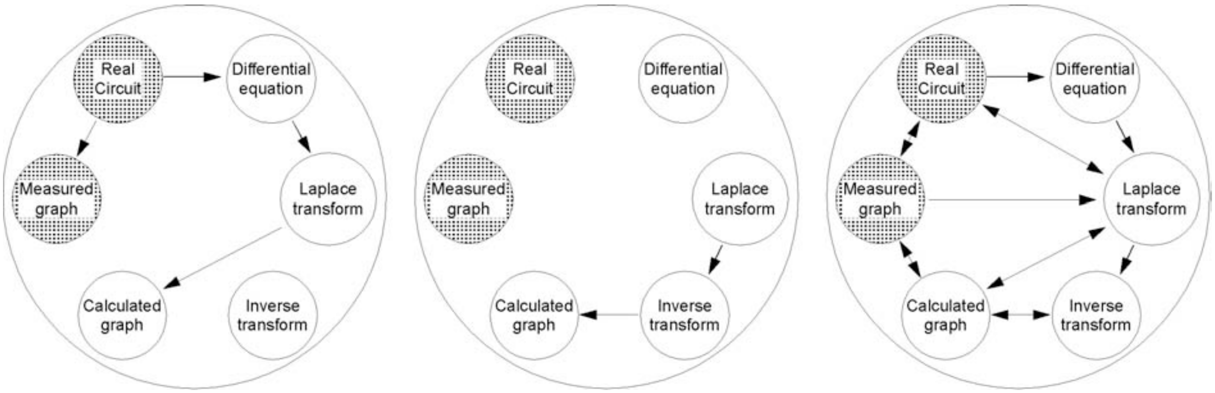


Figure 14**. An example of an analysis of learning in the Transient Response lab, using the model for learning a complex concept:* ***a) *Student Benny's lived object of learning after the first part of the revised lab:* ***b)*** *Student Tess's lived object of learning at the same time; and* ***c)*** *Students Benny and Tess's lived object of learning at the end of the lab work in the revised lab.*

Common features of both of the implementations described above were the measurement, and the modelling of the step-response of the current through the RLC-circuit. In the first implementation, this measurement and modelling were the students' main tasks, which included variance in the value of R, but not in the L and C-values or the circuit topology. The variance in R led to variance in the characteristics of the step-response. From our analysis we found that, although it was our intended object of learning, in the first implementation of the Transient Response lab students did not establish the links displayed in figure 14c. Students' lived object of learning did not correspond to the intended object of learning. Students did not, in the first implementation, discern all the critical aspects.

In the second implementation of the lab the task described in figure 13 preceded the measurements of the RLC-circuit. Our analysis showed that the variance introduced in this task was vital for students to be able to identify the critical aspects of the object of learning. Marton et al.[1] point out

> "[v]ariation that is not present in the situation can still be discerned … if variation is brought in by means of … previous experience" (p. 21).

They also point out that (p. 30)

> "it is very important that the teacher is able to bring critical features of the object of learning into students' focal awareness".

By introducing the tasks before the measurements, in the design of the second implementation, critical features of the object of learning were introduced to the students' awareness.

In the new course, the students knew that there was time for both calculations and lab work, and they demonstrated this awareness by working differently. The trial-and-error behaviour seen in the old course disappeared. At the beginning of this session the discussions within and between groups concerned the subject matter. They very soon found patterns which made it possible for them to compare the calculated graphs and the measured graphs[87].

CONCLUSIONS AND IMPLICATIONS

The conclusions from our work regarding the electric circuit theory course and the mechanics have several important implications for future designs. Firstly, integrating the lab sessions and the problem-solving sessions, as done in the electric circuit theory course, gives students new ways to handle the subject matter. They bring their knowledge from the mathematical context into the lab, but can also use the graphs when elaborating the mathematical context. When simultaneously working from the object/event world, and the theory/model worlds, the students make the vital link. Consequently, the focus of the lab work is changed. Instead of focusing on what to report, the students now focus on what is to be learned, i.e. they make links between all the components of the circle in our model. Our results from the mechanics course as well as the electric circuit theory course show that labs can be designed to be an arena that opens up for active learning. Contrary to the electric circuit theory course the mechanics course the scheduling format of traditional labs were kept. However, our data show that the re-design of the tasks within this format have led to much higher achievements on conceptual test. We propose that these insights could be implemented in re-designing learning environments in other domains.

Secondly, the study shows the importance of conducting a fine-grained analysis of students' courses of action in education. Without such careful analysis, we would not have seen that our intended object of learning was not the enacted object of learning in the first implementation of the lab. Our results show that our model of learning of a complex concept, and Marton's theory of variation, are valuable tools for analysing the lived object of learning. Our results also indicate that using the theory of variation is useful in the design and improvement of learning environments. Existing learning environments could be analysed by examining the kind of variation that is afforded by the design, if any. These findings could then be taken into account, as we have done, by re-designing the learning environment to introduce the required variation that was missing in the original design. Thus, the enacted object of learning is improved, leading to an improved lived object of learning.

Thirdly, our results corroborate that the links between the object/event world and the theory/model world have to be made explicit in lab work.

Fourth, our research shows that neither mechanics nor Laplace transforms are too difficult to teach and learn, and that it is possible for students to attain a functional understanding of mechanics as well as transient responses.

Fifth this study shows clearly that design experiments are able to contribute to theory development as well as improvement of the practice of engineering education.

Finally this study suggest that designing engineering education and researching engineering education should be seen as an engineering practice and as engineering research. We should remember the words of Mitcham[11]:

> "artifact design is what constitutes the essence of engineering. … Technology is not so much the *application* of knowledge as a *form* of knowledge …".

Designing for learning is thus in the essence of engineering.

ACKNOWLEDGEMENTS

Grants from the Swedish Research Council and the Council for Renewal of Higher Education are gratefully acknowledged. Anna-Karin Carstensen gratefully acknowledges support from the Swedish National Graduate School in Science and Technology Education.

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