Linköping Studies in Science and Technology, Dissertation No. 1529
Studies in Science and Technology Education, No. 67

CONNECT

Modelling Learning to Facilitate Linking Models and the Real World trough Lab-Work in Electric Circuit Courses for Engineering Students

Anna-Karin Carstensen

Linköping University

Engineering Education Research Group
Department of Science and Technology (ITN)
Campus Norrköping, Linköping University, Sweden

Norrköping 2013

The research reported in this dissertation has been funded by the Swedish National Graduate School in Science and Technology Education (FontD), Jönköping School of Engineering and by the Swedish Research Council through grants VR 2003-1208, VR 2003-4445 and VR 2011-5570 which is gratefully acknowledged.

Connect
– Modelling Learning to Facilitate Linking Models and the Real World through Labwork in Electric Circuit Courses for Engineering Students

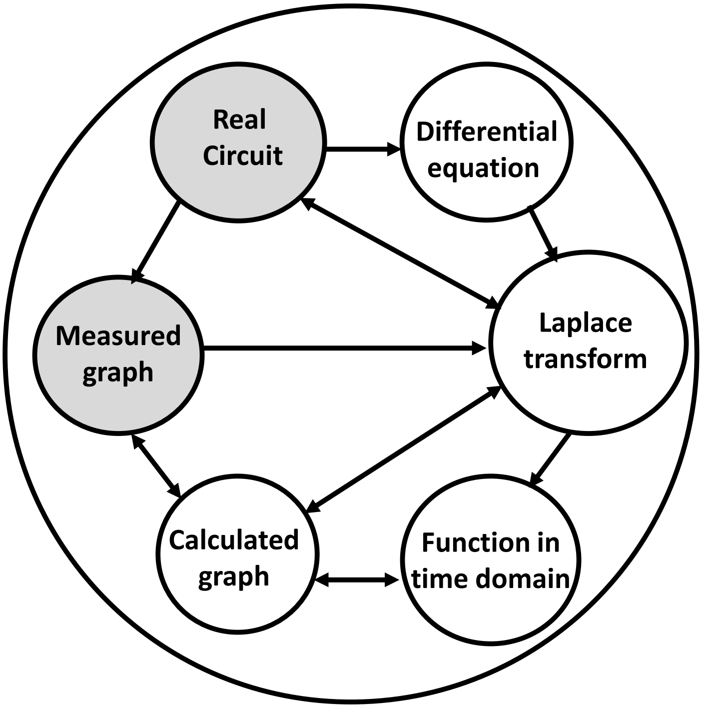
Distributed by:
Engineering Education Research Group
Department of Science and Technology (ITN)
Campus Norrköping, Linköping University
SE-60174 Norrköping, Sweden

This dissertation is available in electronic form at Linköping University Electronic Press: www.ep.liu.se

Cover/picture/Illustration/Design: Anna-Karin Carstensen

Printed in Sweden by LiU-Tryck, Linköping, Sweden, 2013

ISBN: 978-91-7519-562-9
ISSN: 0345-7524
ISSN: 1652-5051


Real Circuit
Differential equation
Measured graph
Laplace transform
Calculated graph
Function in time domain

Sammanfattning

En stående fråga som lärare i naturvetenskapliga och tekniska utbildningar ställer är varför elever och studenter inte kopplar samman kunskaper från teoretiska kursmoment med den verklighet som möts vid laborationerna. Ett vanligt syfte med laborationer är att åstadkomma länkar mellan teori och verklighet, men dessa uteblir ofta.

Många gånger används avancerade matematiska modeller och grafiska representationer, vilka studenterna lärt sig i tidigare kurser, men de har sällan eller aldrig tillämpat dessa kunskaper i andra ämnen. En av dessa matematiska hjälpmedel är Laplacetransformen, som främst används för att lösa differentialekvationer, och åskådliggöra transienta förlopp i ellära eller reglerteknik. På många universitet anses Laplacetransformen numera för svår för studenterna på kortare ingenjörsutbildningar, och kurser eller kursmoment som kräver denna har strukits ut utbildningsplanerna. Men, är det för svårt, eller beror det bara på hur man presenterar Laplacetransformen?

Genom att låta studenterna arbeta parallellt med matematiken och de laborativa momenten, under kombinerade lab-lektionspass, och inte vid separata lektioner och laborationer, samt genom att variera övningsexemplen på ett mycket systematiskt sätt, enligt variationsteorin, visar vår forskning att studenterna arbetar med uppgifterna på ett helt annat sätt än tidigare. Det visar sig inte längre vara omöjligt att tillämpa Laplacetransformen redan under första året på civilingenjörsutbildning inom elektroteknik.

Ursprungliga syftet med avhandlingen var att visa

- hur studenter arbetar med laborationsuppgifter, speciellt i relation till målet att länka samman teori och verklighet
- hur man kan förändra studenternas aktivitet, och därmed studenternas lärande, genom att förändra laborationsinstruktionen på ett systematiskt sätt.

Under våren 2002 videofilmades studenter som utförde laborationer i en kurs i elkretsteori. Deras aktivitet analyserades. Speciellt studerades vilka frågor studenterna ställde till lärarna, på vilket sätt dessa frågor besvarades, och på vilket sätt svaren användes i den fortsatta aktiviteten.

Detta ledde fram till en modell för lärande av sammansatta begrepp, som kunde användas både för att analysera vad studenterna gör och vad lärarna förväntar sig att studenterna ska lära sig. Med hjälp av modellen blev det då möjligt att se vad som behövde ändra i instruktionerna för att studenterna lättare skulle kunna utföra de aktiviteter som krävs för att länka teori och verklighet.

Syftet med avhandlingen är därmed att

- ta fram en modell för lärande av ett sammansatt begrepp
- visa hur denna modell kan användas för såväl analys av önskat lärandeobjekt, som av studenternas aktivitet under laborationer, och därmed det upplevda lärandeobjektet
- använda modellen för att analysera vilka förändringar som är kritiska för studenters lärande.

Modellen användes för att förändra laborationsinstruktionerna. Lärarinterventionerna inkluderades i instruktionerna på ett systematiskt sätt utifrån dels vilka frågor som ställdes av studenterna, dels vilka frågor studenterna inte noterade, men som lärarna velat att studenterna skulle använda för att skapa relationer framför allt mellan teoretiska aspekter och mätresultat. Dessutom integrerades räkneövningar och laborationer.

Videoinspelningar utfördes även våren 2003, då de nya instruktionerna användes. Även dessa analyserades med avseende på studenternas aktiviteter. Skillnader mellan resultaten från 2002 och 2003 står i fokus.

- Avhandlingens resultatdel består av:
- Analys av studenternas frågor och lärarnas svar under labkursen 2002
- Analys av de länkar studenterna behöver skapa för att lära
- Analys av laborationsinstruktionerna före och efter förändringarna
- Analys av den laborationsaktivitet som blev resultatet av de nya instruktionerna, och vilket lärande som då blev möjligt

Avhandlingen avlutas med en diskussion om de slutsatser som kan dras angående möjligheter att via forskning utveckla modeller av undervisningssekvenser för lärande där målet är att länka samman teori och verklighet

Abstract

A recurring question in science and engineering education is why the students do not link knowledge from theoretical classes to the real world met in laboratory courses.

Mathematical models and visualisations are widely used in engineering and engineering education. Very often it is assumed that the students are familiar with the mathematical concepts used. These may be concepts taught in high school or at university level. One problem, though, is that many students have never or seldom applied their mathematical skills in other subjects, and it may be difficult for them to use their skills in a new context. Some concepts also seem to be "too difficult" to understand.

One of these mathematical tools is to use Laplace Transforms to solve differential equations, and to use the derived functions to visualise transient responses in electric circuits, or control engineering. In many engineering programs at college level the application of the Laplace Transform is considered too difficult for the students to understand, but is it really, or does it depend on the teaching methods used?

When applying mathematical concepts during lab work, and not teaching the mathematics and practical work in different sessions, and also using examples varied in a very systematic way, our research shows that the students approach the problem in a very different way. It shows that by developing tasks consequently according to the Theory of Variation, it is not impossible to apply the Laplace Transform already in the first year of an engineering program.

The original aim of this thesis was to show:

- how students work with lab-tasks, especially concerning the goal to link theory to the real world
- how it is possible to change the ways students approach the task and thus their learning, by systematic changes in the lab-instructions

During the spring 2002 students were video-recorded while working with labs in Electric Circuits. Their activity was analysed. Special focus was on what questions the students raised, and in what ways these questions were answered, and in what ways the answers were used in the further activities.

This work informed the model ”learning of a complex concept”, which was used as well to analyse what students do during lab-work, and what teachers intend their students to learn. The model made it possible to see what changes in the lab-instructions that would facilitate students learning of the whole, to link theoretical models to the real world, through the lab-activities.

The aim of the thesis has thus become to

- develop a model: The learning of a complex concept
- show how this model can be used as well for analysis of the intended object of learning as students activities during lab-work, and thus the lived object of learning
- use the model in analysis of what changes in instruction that are critical for student learning.

The model was used to change the instructions. The teacher interventions were included into the instructions in a systematic way, according to as well what questions that were raised by the students, as what questions that were not noticed, but expected by the teachers, as a means to form relations between theoretical aspects and measurement results. Also, problem solving sessions have been integrated into the lab sessions.

Video recordings were also conducted during the spring 2003, when the new instructions were used. The students' activities were again analysed. A special focus of the thesis concerns the differences between the results from 2002 and 2003.

The results are presented in four sections:

- Analysis of the students' questions and the teachers' answers during the lab-course 2002
- Analysis of the links students need to make, the critical links for learning
- Analysis of the task structure before and after changes
- Analysis of the students' activities during the new course

The thesis ends with a discussion of the conclusions which may be drawn about the possibilities to model and develop teaching sequences through research, especially concerning the aim to link theoretical models to the real world.

Key Words

Engineering Education Research

Learning of a Complex Concept

Key concepts

Variation Theory

Practical Epistemologies

Threshold concepts

Models

Learning to model

Modelling learning

Learning

Laplace Transforms

Lab-work

Engineering Education

Foreword

Born a teacher, in the sense that I have always wanted everyone else to know at least what I know, and therefore tried to explain everything to everybody, it is not strange that I ended up making research in electrical engineering education. In this area very little research is carried out, and many colleagues wondered why I wanted to do this, is this really something for an engineer to do research on. My answer is YES! So many students have had to have problems entering engineering studies, and have asked themselves does it have to be this difficult, and I believe the answer is NO. Research in engineering education is important in order to find out how to make learning possible, instead of the old idea of engineering education that only those who can stand the bad teaching are aimed to become engineers.

In order to do research on topics of engineering education, I believe the researcher has to be as well an engineer as a teacher. Without the engineering knowledge it is impossible to know what is important to learn and where the difficulties lie. To have a deep knowledge of the subject matter, the context where the learned matters are to be used, and also of how it is taught today, are important ingredients in education research: "Learning is always the learning of something" (Ference Marton)

The possibility to carry out this research came with the National Research School in Science and Technology Education, FontD, which started in 2002. Earlier it was very difficult to get funding for this kind of research I wanted to carry out, and colleagues tried to talk me out of the idea. The first person to believe in my idea was Elisabeth Sundin, Arbetslivsinstitutet in Norrköping, who helped me to apply for money, which I unfortunately didn't get, but also made me contact my supervisor, Jonte Bernhard, who was involved in the start-up process for the national graduate school. Suddenly there was a change in how people around me looked upon my research idea. I got additional funding from my employer, the Jönköping School of Engineering, and my colleagues took great interest in what I was doing. When doing research in an area where not many people are engaged it is important to have fellow students, and I want to thank all the students in the FontD for the support and valuable discussions we have had. Although thanking you all I want to give a special thanks to Margareta and Anna who have been kind to read and comment more than one of my early attempts.

At the same time as I started to do this work, two other electrical engineering teachers, Margarita Holmberg and Åsa Ryegård, also started to do research in electrical engineering. Margarita came from Mexico to Barcelona, and we met at ESERA (European Science Education Research Association) summerschool 2002. It was amazing to meet somebody interested in the same questions as those I had. Thank You both for all the interesting discussions we have had, and for the support in the belief that research in electrical engineering education is important.

Now that the Thanks session of the preface has come to the important part where the thanks should be given to the supervisors of the thesis, I don't know what to write. It is impossible to find the words that would give Ference Marton and Jonte Bernhard the credits they deserve.

Thank You Ference for your straight forwardness, your honesty, and your patience. Thank You Jonte for pushing me to a conference already my first year, putting me straight into presenting the research, for letting me do lots of things you didn't believe in, but also for all the discussions. Thank you also for letting me finish after all these years.

Being the only graduate student at my department carrying out research in education, I still want to thank my fellow graduate students at the Engineering School for the discussions we have had about educational matters.

Especially I want to thank my colleague Adam Lagerberg for your interest in my research. Sharing a common interest in control engineering, we had many discussions about control engineering education.

A special thanks goes to Åke Ingerman, who was the discussant at my 90%-seminar. The thesis is a totally different one after your revolutionary change of research question and change of main contribution to the research community. What I considered just being engineering – making a model – is now the main theme in the thesis. Of course the model was a result from research, and I considered it that way, but that the engineering modelling was a research method in education was something you made me see. That research in engineering education is engineering was maybe taken for granted although we have written a paper about that. Thank you Åke for telling me to write more about the things I like to write about and skip those that I had problems with.

A true reader, whom I especially want to thank, is my father Gunnar, who should have been the one taking the degree of a doctor, but never got the chance. Many of the texts during these doctoral studies have been read and commented by him, and without his support this thesis would not have been possible. Thank you mom and dad for giving me the support I needed.

Last but not least I want to thank my family. When starting this journey of research I, my husband Anders and our oldest daughter Anna-Maria had endless discussions about philosophy, discourse, ontology, knowledge, and other topics. Our youngest daughter wasn't interested at the time so she stated our joke: "Diskurs – Disk usch!", meaning that discussions about discourse were as bad as having to wash dishes. Thank You Rebecka for standing our discussions, and helping us when we doubted our ability to carry out the research and the writing of a thesis. Thank You Anders for your support in all kinds of ways. Thank you Anna-Maria, Linnea and Rebecka for your support and comfort; it is really nice for a mother to get the comment: “Du är duktig, mamma!” (“You can do it, mom!”)

Contents

Publications

I have chosen to submit this thesis as a monograph instead as a collection of papers and manuscripts with a comprehensive summary as is typical for a thesis in science and in engineering in Sweden. The format of a monograph "opens up" for an inclusion of extensive transcripts as well as a detailed description of the technical content, the object of learning, the students were supposed to learn. By choosing this format I hope the research I am presenting will be better understood since it could be presented as a whole and not by its pieces.

Nevertheless my research has been published in several papers and presented at several conferences as is clear from the list below excerpted from the "anmälan av disputation“ (Application for public defence of PhD Dissertation) made by my supervisor professor Jonte Bernhard. As is noted in the text of the thesis, parts of these papers make up parts of the thesis.

Published papers in scientific journals (incl. Book chapters with peer review) within the scope of the thesis

Carstensen, A.-K., and Bernhard, J. (2007). Critical aspects for learning in an electric circuit theory course - an example of applying learning theory and design-based educational research in developing engineering education. Distributed journal proceedings from the International Conference on Research in Engineering Education, published in the October 2007 special issue of the *Journal of Engineering Education*, 96(4).

Carstensen, A.-K., and Bernhard, J. (2008). Threshold concepts and keys to the portal of understanding: Some examples from electrical engineering. In R. Land, E. Meyer and J. Smith (Eds.), *Threshold Concepts within the Disciplines* (pp. 143-154). Rotterdam: Sense Publishers.

Carstensen, A.-K., and Bernhard, J. (2009). Student learning in an electric circuit theory course: Critical aspects and task design. *European Journal of Engineering Education*, *34*(4), 389-404.

Carstensen, A.-K., and Bernhard, J. (manuscript). *Make links: The missing link between variation theory and practical epistemologies.* Preliminary accepted as book chapter full version to be submitted Sept. 15 2013.

Full papers presented at conferences with peer review

This is merely a selection and only conferences with full papers (no abstracts or extended abstracts) are included

Carstensen, A.-K., and Bernhard, J. (2002). *Bode Plots not only a tool of engineers, but also a key to facilitate students learning in electrical and control engineering*. PTEE 2002: Physics Teaching in Engineering Education, Leuven.

Carstensen, A.-K., and Bernhard, J. (2004). *Laplace transforms - too difficult to teach learnand apply, or just matter of how to do it.* EARLI sig#9 Conference, Göteborg.

Carstensen, A.-K., Degerman, M., González Sampayo, M., and Bernhard, J. (2005). *Interaction in Labwork - linking the object/event world to the theory/model world (Symposium).* ESERA2005, Barcelona.

Carstensen, A.-K., and Bernhard, J. (2008). *Keys to learning in specific subject areas of engineering education - an example from electrical engineering.* SEFI 36th Annual Conference, Aalborg.

Bernhard, J., Carstensen, A.-K., and Holmberg, M. (2011). *Analytical tools in engineering education research: The "learning a complex concept" model, threshold concepts and key concepts in understanding and designing for student learning.* Paper presented at the Research in Engineering Education Symposium, Madrid.

Carstensen, A.-K., and Bernhard, J. (2013). *Make links: Learning complex concepts in engineering education.* Paper presented at the Research in Engineering Education Symposium, Kuala Lumpur.

Published papers in scientific journals (incl. Book chapters with peer review) within the scope of the thesis, of relevance, but not included in the thesis

Bernhard, J., Carstensen, A.-K., and Holmberg, M. (2010). *Investigating engineering students' learning: Learning as the 'learning of a complex concept'*. IGIP-SEFI 2010, Trnava.

Bernhard, J., Carstensen, A.-K., and Holmberg, M. (2013). *Understanding phase as a key concept in physics and electrical engineering*. SEFI 2013, Leuven.

1 Introduction

Why don't students link knowledge from theoretical sessions with the real world they meet in lab-sessions? Although one of the most common aims of lab-work is to get students to make links between the theory/model world and the object/event world, this does not happen (Tiberghien, 2000).

In engineering education, mathematical models are widely used, and it is necessary to be skilled in relating mathematical models to different kinds of problems in many settings, e.g. Fourier Transforms and Fourier series to calculate frequency responses in electronics, telecommunication and control theory, differential equations in physics, control theory and construction, logics and discrete mathematics in computer science. There is a common belief, as in science education (Tiberghien, Veillard, Le Marechal, Buty, & Millar, 2001) that lab work will make students understand theory presented in lectures, by making links between theoretical content and practical work, during lab-sessions. Often, when students fail, the assumption is that they are not good enough in mathematics, and in some cases the mathematics laden courses are simply withdrawn from the curriculum, as is e.g. the case with control theory in shorter engineering programs[1] at many universities in Sweden.

The particular content knowledge in this study is transient response, and how students understand that phenomenon (in the object/event world) in relation to the Laplace transform (in the theory/model world). This is part of a course in electric circuit theory, given in the first year of an electrical engineering education program.

When teachers talk about the learning through labs, they often discuss it in terms of links between theory and practice, or declarative versus procedural knowledge. The divide between theoretical and practical work is analytically problematic, since laboratory processes may include theoretical considerations, and theoretical modelling may include procedural knowledge, or skills. Tiberghien (2000) has developed another categorisation of knowledge: the theory/model world and the object/event world. (cf. Figure 1)

---

[1] Engineering programs in Sweden were either 3 years (bachelor's degree, "högskoleingenjör") or 5 years (master's degree, "civilingenjör"). The Bologna process in Europe has changed all university programs into two parts, 3+2 years, but when this study was carried out, students either signed up for a 3 year or a 5 year program, and the 3 year programs were a little less theoretical.

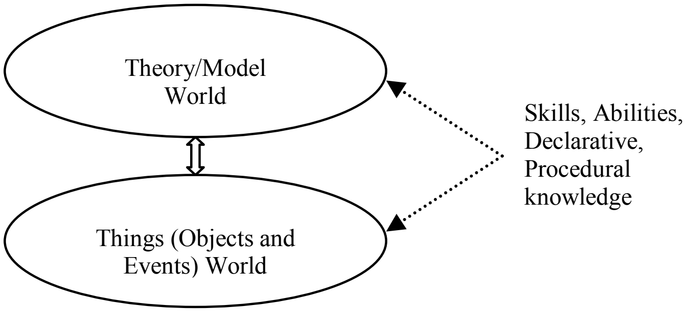


Figure 1: Categorisation of knowledge based on a modelling activity (Tiberghien, 2000)

The aim of lab work is usually, although not often explicitly stated in instructions (Tiberghien et al., 2001), to facilitate for students to make links between the two worlds.

Modelling is an enterprise which is commonly carried out in science and engineering. Models are used either to understand something that is difficult or impossible to see, as in science when e.g. visualisations of molecules is used, or models are used to analyse something without having to carry out experiments. When they are used in the latter sense they are often used because it is not possible or not feasible to make experiments, e.g. testing of aerodynamics in wind tunnels. In recent research it has been pointed out that it is important for learning as well in school science (e.g. Brna, Baker, Stenning, & Tiberghien, 2002; Redfors & Ryder, 2001; Andrée Tiberghien, Jacques Vince, & Pierre Gaidioz, 2009), as in higher education (e.g. Gerlee & Lundh, 2012; Haglund, 2012) and in industrial engineering (Malmberg, 2007) to understand models. Models of different types are used: verbal, conceptual, mental, visual or mathematical models. In education models are taught as representations, where it is important that students understand that the models are representations and not the "real thing", and many recent researchers in science education have been dealing with this issue. One of the most recognized characteristics of models and modelling is the possibility to predict dynamic behaviour. In engineering education (as well as in advanced science education) several different models may be used in order to understand one complex concept, and students are expected to learn how to use the appropriate model. Malmberg (2007) shows how it is necessary for engineers not only to know the models, but also when to use them, i.e. how to choose among them depending on when in a design process the model is to be used. He models as well the electronic circuits as the engineering process, and discusses how this leads to more expert like behaviour.

In this thesis a model of learning is in focus. A model of *learning of a complex concept* is developed and analysed. The model is a model of what the students do during lab-work, and the model is as well derived from, as validated through the analysis of videorecordings from lab work in a first year course in electric circuits for electrical engineering students. The model is also used to analyse what students do not do or talk about, which is shown to be a valuable tool in the development of new lab-instructions. This model is not to be confused with mental models, which try to show what students have learned, but a conceptual model which may be used to analyse:

- the learning pathways that students take, the lived object of learning
- the complex concept in terms of as well concepts as actions - the intended object of learning
- what actions could facilitate for students to learn the complex concept.

Earlier research has shown that teacher interventions are of uttermost importance to the students' ways to approach learning and also to their activities during lab-work (e.g. Barnes, 1976; Bowden & Marton, 1998; Buty, Tiberghien, & Le Marechal, 2004; Malmberg, 2007; Wickman & Östman, 2002). Is it also possible to include the teacher interventions in the lab-instructions?

Although the first aim of this thesis was to show:

- how students work with lab-tasks, especially concerning the goal to link theory to the real world
- how it is possible to change the ways students approach the task and thus their learning, by systematic changes in the lab-instructions

the use of the model *the learning of a complex concept*, gave a more elaborated research proposition:

- to develop a model: The learning of a complex concept
- show how this model can be used as well for analysis of the intended object of learning as students activities during lab-work, and thus the lived object of learning
- use the model in analysis of what changes in instruction that are critical for student learning.

Learning is according to variation theory “changing ones way of experiencing some phenomenon and teaching is hence creating situations where such change is fostered” (Booth, 2004, p. 9). In order to learn the student has to discern critical aspects of the concept or phenomenon to be learned, and in order to discern something it is necessary that these aspects are varied in a systematic way. Variation theory has used two research methods, phenomenography and learning studies, the former used interviews with students, the latter a series of lessons where the teaching sequence was altered in an iterative process engaging as well teachers as a researcher. In this study we wanted to explore students’ activities in the laboratory, especially regarding the links between the two worlds. We studied as well what questions were raised by the students, as what questions that were not noticed, but expected by the teachers, as a means to form relations between theoretical aspects and measurement results. Practical epistemologies (Wickman, 2004) is a method especially aimed at studying gaps between what students already know and what is new in the lab-situation. The method makes it possible to study as well what students notice, as what they do not notice, and which gaps that are filled by creating relations or are not filled and thus linger.

Although relying on different philosophical basis, the contingency of these two theoretical frameworks give results that are valid for learning the complex concepts in engineering education.

Normally the theoretical background will be the first chapter of a thesis, but here the thesis will start with an introduction to what the intended object of learning is, from a teacher's point of view. The reason for such a chapter is that the object of learning often is taken for granted in a community of teachers in that subject, but that most researchers in education are not familiar with the particular object of learning presented in this thesis (Bowden & Marton, 1998). In order to see what there is to learn, and whether this is learned the researcher has to know the content well, needs to be able to see what aspects that are critical, both for an engineer to know and for the student to learn (Emanuelsson, 2001).

The theoretical background will include a chapter on philosophical considerations on technology education, a description of the three main theories on which my study relies: practical epistemologies, variation-theory and threshold concepts and a chapter on my contribution to theory: *key concepts* - a developing theoretical framework which suggests implications for future research.

Research in engineering education is a rather new enterprise (cf. Baillie & Bernhard, 2009 and; Borrego & Bernhard, 2011), and very little is written on the specific subject area, electrical engineering. I will include a chapter on engineering education, where I present some earlier research which shows why there is so little research in the area, but also why it is important for engineers to carry out research in specific engineering education domains.

After this, the setting of the empirical study is explained. Video recordings were made during labs before and after changes in the instructions.

The main contribution of this research is *the model of learning of a complex concept.* This requires a chapter describing modelling as the research method. As well the model as the modelling process are discussed.

This thesis consists of four studies, one where the model is developed, and three where the model is used to analyse students' learning in terms of links, i.e. relationships between concepts, critical aspects in the lab-tasks, and finally the new discourse that was a result from the changes in lab-instructions. The different studies are using different methods, or combinations of these. To use a model in different ways and especially to use it for prediction and then test the outcome, is as well giving new results as validating the model and thus the results

The results from the four studies are presented in four sections:

- What questions are raised during lab-work: Analysis of the students' questions and the teachers' answers during the lab-course 2002
- Make links: Analysis of the links students need to make, the critical links for learning
- Task structure: Analysis of the task structure before and after changes
- New discourse: Analysis of the students' activities during the new course

Models as well as research results need to be validated, and in the discussion a section will be dedicated to the question of validity. The thesis ends with a discussion of the conclusions which may be drawn about the possibilities to develop teaching sequences through research, especially concerning the aim to link theoretical models to the real world.

2 The intended object of learning – Transient Response

This type of chapter is not commonly found in a thesis. The object of learning is a, by teachers commonly agreed upon, taken for given, or at least considered that way. Since transient response is an area from a discipline, seldom subject to research in education, a demand to explain the content area from a teacher's point of view has become necessary. To describe *a taken for a given* is not an easy task, and seldom required, which makes it difficult to handle in a thesis. Does it need to be a separate aim for the research or is it enough to describe what comes out implicitly, while doing research on what is going on in the learning sessions? The description below tries to give a reflective teacher's view of what the intended object of learning is. Although some of the findings stem from the research on students' understanding, it has not been the main focus of the research presented in the thesis to investigate what teachers have agreed upon, but should be seen as a brief exploration of the intended understanding. The chapter ends with a short summary of how the subject is presented in three textbooks commonly used in electrical engineering education, in order to give a picture of how reliable the *taken for granted* may be considered.

The intended object of learning is a term borrowed from the theory of variation, and relates to what the teachers have intended for the learners to learn. One way to describe this is as a course description in the official curriculum, but there regarding the objectives, rather than the object of learning. The objectives are described from the learning outcomes point of view, whereas *the object of learning* is rather describing what objects, parts a learning object consists of, and how these are related, the *parts/whole relationship* (Marton & Morris, 2002b). Here the intended object will only be described from the reflective teacher's point of view, although one of the studies in the thesis was to investigate critical aspects of this intended object of learning.

Again, this is not a chapter commonly seen in a thesis, because normally the taken for granted is allowed to be taken for granted, but in the case of disciplinary knowledge, it becomes questioned by those not belonging to the discipline. A reader may ask why this chapter is not showing any evidence from research, but from the viewpoint of the discipline, that research is not asked for.

2.1 Why do we teach this mess?

At several occasions when this research has been presented, educationalists have asked why the Laplace Transform is still taught when it seems so difficult. Is it really necessary to teach and to learn? The only seminar where this question was not raised was a seminar where 50 teachers in electrical and control engineering had gathered to listen to a presentation of and discuss our research. When colleagues in educational research present their findings, e. g. what is critical when the object of learning is the clock and time (Holmqvist, Gustavsson, & Wernberg, 2007), nobody asks why we still teach children the clock and time; no one argues that this would be unnecessary knowledge. Thus the research can focus the critical aspect, which in the case of learning about the clock and time was found to be to start by learning the *time hand*. That the learning of the Laplace transform is important, and problematic can easily be argued since, the four rather recently presented research projects in electrical engineering (Carstensen & Bernhard, 2004; Flanagan, Taylor, & Meyer, 2010; González Sampayo, 2006; Lamont, Chaar, & Toms, 2010) all deal with the use of the Laplace transform and the sub-domain, handling complex numbers.

Transient response is the analysis of the output from a system, when the input to the system is suddenly changed, e.g. to estimate what happens to the current when the cord to a vacuum cleaner is pulled out from the wall while still running, or how the temperature in a room changes when a heater is switched on. Transient response is referred to as one of the more difficult parts of electric circuits, and skipped in many engineering curricula especially at college level. What makes it difficult is that the mathematics used is rather advanced, using the Laplace Transform to solve differential equations. Very often the mathematics is handled in the maths course and in the problem solving sessions, the graphs in the lab course and the conceptual understanding of the transients in the lectures, and still it is expected that the students should make links between them.

In previous research it is suggested that "the specific difficulties that students encounter in electronics is that they are faced with contrasting representations or models of a circuit – the actual circuit, the circuit diagram, simplifying transforms of it, algebraic solutions, and computer simulations (Entwistle et al. 1989). Students have to move between these different representations in solving problems or designing circuits and they also need to understand the function of a circuit in both practical and theoretical ways – the engineering application and the physics of how it behaves." (Entwistle, Hamilton, et al., 2005). These problems occur already in the prerequisite course, electric circuits, which is the actual course in this research.

The main reason for teaching the Laplace Transform is that it facilitates the solving of differential equations. Some of the differential equations would not be possible to solve without the use of the Laplace transform, e. g. when the differential equation contains the derivative of a discontinuous function, which is the case when working with transients. (González Sampayo, 2006) discusses three levels of engineering knowledge, basic concepts, analysis, and design, and argues that it is important to consider at which level the knowledge needs to be learned. To learn the Laplace transform in itself is thus at the basic level, whereas to learn to use it in the electric circuit course is to use it as a tool to analyse and predict the behaviour of a circuit, and to use the Laplace transform in control engineering or a filter design course would be to use it as a design tool. At the basic level, González claims that concepts are learned as separate islands, but in order to use concepts in analysis and design it is important that concepts are linked (González Sampayo, 2006). In the case of transient response, this would be to be able to predict the step response from a real circuit (in the time domain) when a model of it, the transfer function (Laplace transform, in the frequency domain) is given.

2.2 A model of the intended object of learning

The intended object of learning, when working with the Laplace transform to solve the differential equations, is to learn and reflect on the chain from the real circuit through the mathematics onto the graph derived mathematically, to compare this graph with the measured graph and thus relate back to the real circuit again. This can be illustrated by the chain below:

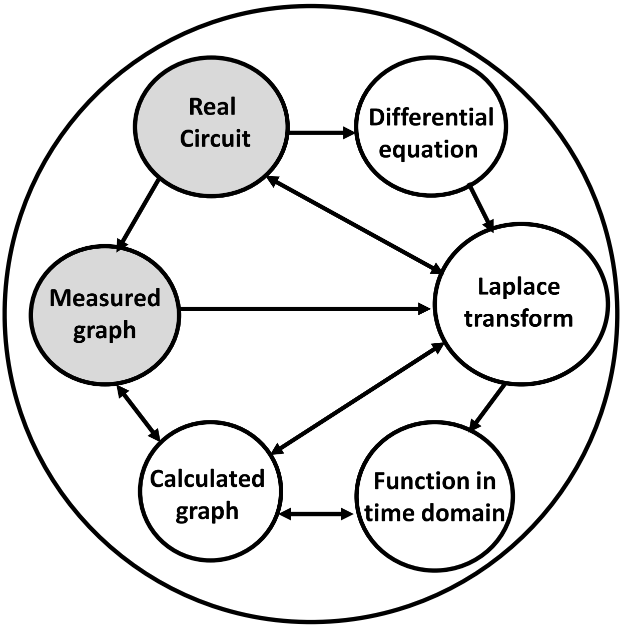


Figure 2: The intended object of learning

The arrows in figure 2 show the links that the teacher expects the students to make. The figure above is a result from the research, and not a coherent teaching strategy commonly used by teachers. Studying the chapters in a text book in electric circuit theory, they would typically reflect the object of learning as the circles above, although not systematically or explicitly taught in the circular manner, and the main aim with the labs is that students make links between the nodes, although this aim seldom is explicitly stated.

2.3 Description of the concepts involved in the transient lab

Large parts of this this chapter is from a paper published in, Carstensen and Bernhard (2009)

The students are measuring the output voltage from and the current through an electric circuit in which a resistor is put in series with an inductor and a capacitor:

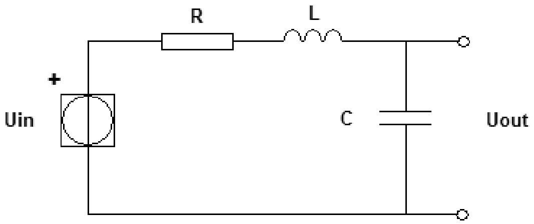
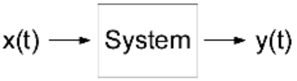


Figure 3: The electric circuit used in the transient response lab.

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. The explicit task posed in the lab instruction is to make a curve fit, which 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. A computer program, Data Studio™, is used to get both curves into the graph.

It is often convenient to regard an electric circuit as a system that transforms one or more input signals *x(t)* into one or more output signals *y(t)* (see Figure 4). The signals may be as well voltages as currents.



$$Y(s) = G(s) \cdot X(s)$$

$G(s) =$ transfer function

Figure 4: The circuit viewed as a system

The output $y(t)$ is dependent on both the specific input signal $x(t)$ and the system's characteristics, and this dependency can be quite difficult to work through in the time domain since differential integral equations may be involved. However, if Laplace transforms of the input $x(t)$ and output $y(t)$ are used, $X(s)$ and $Y(s)$ respectively, this dependency can be expressed as $Y(s) = G(s) \cdot X(s)$, where $G(s)$ is known as the transfer function. Notably, the transfer function $G(s)$ only depends on the system.

In most cases the transfer function can be written as a ratio of two polynomials:

$$G(s) = \frac{B(s)}{A(s)} = \frac{b_m s^m + b_{m-1} s^{m-1} + \cdots + b_1 s + b_0}{a_n s^n + a_{n-1} s^{n-1} + \cdots + a_1 s + a_0} = K \frac{(s + z_1)(s + z_2) \cdots (s + z_m)}{(s + p_1)(s + p_2) \cdots (s + p_n)}$$

Here, z_i are zeros and p_i are the poles of the system, which are important in determining the response characteristics. They are either real or exist in complex conjugate pairs, since a_i and b_i are real for all physical systems. Complex conjugate poles, $\sigma \pm j\omega_d$, will give cause to contributions (in the time-domain) in the form $k\cdot e^{\sigma t}\sin(\omega_d t+\varphi)$ and distinct real poles, p, in the form $k\cdot e^{pt}$.

The general form of the transfer function for a second order system is:[2]

$$G(s) = \frac{b_2 s^2 + b_1 s + b_0}{a_2 s^2 + a_1 s + a_0}$$

The above theory is general and applicable to many types of systems, e.g. biology, economy, and not only those used in electrical and control engineering. For instance, both a simple *RLC*-circuit and a spring with a viscous damping are examples of second order systems (n=2).

The differential equations for the circuit in the lab are:

$$u_{in}(t) = \sigma(t) = \begin{cases} 1, t \geq 0 \\ 0, t < 0 \end{cases}$$

$$\begin{cases} C \cdot \dfrac{du_{out}(t)}{dt} = i(t) \\ u_{in}(t) = R \cdot i(t) + L \cdot \dfrac{di(t)}{dt} + u_{out}(t) \end{cases}$$

which for the relation between input voltage, u_{in}, and the capacitor voltage, u_{out}, gives the expression

$$u_{in}(t) = RC\frac{du_{out}(t)}{dt} + LC\frac{d^2u_{out}(t)}{dt^2} + u_{out}(t) \Rightarrow$$

$$\frac{d^2u_{out}(t)}{dt^2} + \frac{R}{L}\frac{du_{out}(t)}{dt} + \frac{1}{LC}u_{out}(t) = \frac{1}{LC}u_{in}(t)$$

and for the relation between input voltage and the current through the circuit gives:

$$u_{in}(t) = Ri(t) + L\frac{di(t)}{dt} + \frac{1}{C}\int_{-\infty}^{t} i(t)dt \Rightarrow$$

$$RC\frac{di(t)}{dt} + LC\frac{d^2i(t)}{dt^2} + i(t) = C\frac{du_{in}(t)}{dt}$$

One of the tasks in the lab is to experimentally and mathematically determine $i(t)$ and the voltage across the capacitor $u_{out}(t)$, when $u_{\text{in}}(t)$ is a voltage step. However, many students find it difficult to obtain the solutions by solving the differential equations, and in the case when

---

[2] In circuit theory, control theory, and physics, $G(s)$ for a second order system is often expressed by using one of the special forms: $G_1(s) = B(s)/(s^2 + 2\alpha s + \omega_n^2)$ or $G_2(s) = B(s)/(s^2 + 2\zeta\omega_n s + \omega_n^2)$. Note however that the parameters in these (or similar) forms of modelling are only applicable to a second-order system. In addition, the damping ratio ζ in the second type of expression is not an independent parameter, but coupled to the natural frequency of the undamped system ω_n, since $\zeta = a_1/(2\omega_n)$. Conversely, poles and zeros can be used to determine the responses and stability of systems of any order, from first to higher order systems, and are therefore more generally applicable. Hence, neither $G_1(s)$ nor $G_2(s)$ is part of our object of learning.

$u_{in}(t)$ is a discontinuous function, here a step-function, it is not even possible without the Laplace transform, since $\frac{du_{in}(t)}{dt}$ is not possible to derive.

But, when using standard procedures for Laplace transforms, the differential equations can be written as:

$$\begin{cases} s^2 U_{out}(s) + \frac{R}{L} s U_{out}(s) + \frac{1}{LC} U_{out}(s) = \frac{1}{LC} U_{in}(s) \\ U_{in}(s) = \frac{1}{s} \end{cases} \Rightarrow$$

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

and

$$\begin{cases} (s^2 LC + sRC + 1) I(s) = sCU_{in}(s) \\ U_{in}(s) = \frac{1}{s} \end{cases} \Rightarrow$$

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

Thus the differential equation is transformed into an algebraic expression in terms of the complex frequency *s*.

The solution (in terms of *s*) can then be transformed back to the time-domain by using the inverse Laplace transform. The Inverse Laplace transform is derived by first finding partial fractions, and after that using transform tables for the Laplace transforms (found in text books and mathematics handbooks)

There will be three kinds of solutions depending on the roots to $s^2 + \frac{R}{L}s + \frac{1}{LC} = 0$

Solving the differential equations for u_{out} gives:

$$\begin{cases} u_{out}(t) = a(1 - e^{bt} \sin(ct + d)) \\ u_{out}(t) = a(1 - te^{bt}) \\ u_{out}(t) = a(1 - (e^{bt} - e^{dt})) \end{cases} \quad \text{for} \quad \begin{cases} \frac{1}{LC} > \left(\frac{R}{2L}\right)^2 \\ \frac{1}{LC} = \left(\frac{R}{2L}\right)^2 \\ \frac{1}{LC} < \left(\frac{R}{2L}\right)^2 \end{cases}$$

Solving the differential equations for $i(t)$ instead of $u_{out}(t)$ gives

$$\begin{cases} i(t) = ae^{bt}\sin(ct+d) \\ i(t) = ate^{bt} \\ i(t) = ae^{bt} + ce^{dt} \end{cases} \quad \text{when} \quad \begin{cases} \dfrac{1}{LC} > \left(\dfrac{R}{2L}\right)^2 \\ \dfrac{1}{LC} = \left(\dfrac{R}{2L}\right)^2 \\ \dfrac{1}{LC} < \left(\dfrac{R}{2L}\right)^2 \end{cases}$$

Since the probability of finding $\frac{1}{LC} = \left(\frac{R}{2L}\right)^2$ in real measurements is very low, there are basically two qualitatively different solutions, rendering two qualitatively different graphs. Depending on the value of the resistor the graph will show one or the other of the two different curves:

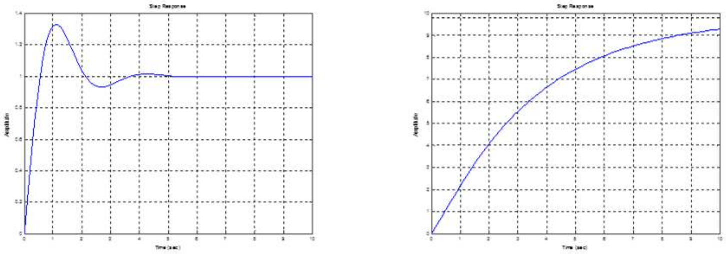


Figure 5: The two qualitatively different curves that can be obtained as output voltage.

The actual values obtained in the lab tasks are calculated in Table 1 and the actual measured curves are shown in Figure 6 below

R_{res} (Ω)	R_{tot} (Ω)	L (mH)	C (µF)	Roots of $s^2 + \frac{R_{tot}}{L}s + \frac{1}{LC}$		$i(t)$ (A)
0	6	8.2	100	$-366 + 1042j$	$-366 - 1042j$	$0.1170e^{-366t}\sin(1042t)$
10	16	8.2	100	$-976 + 517j$	$-976 - 517j$	$0.2357e^{-976t}\sin(517t)$
33	39	8.2	100	-272	-4484	$0.0290(e^{-272t} - e^{-4484t})$
100	106	8.2	100	-95	-12832	$0.0096(e^{-95t} - e^{-12832t})$

Table 1: Variations in terms of R_{res}, with L, C, and E constant. Note that the frequency, ω_d, of the damped system changes with R and is not equal to ω_n. (Carstensen & Bernhard, 2009, p. 403)

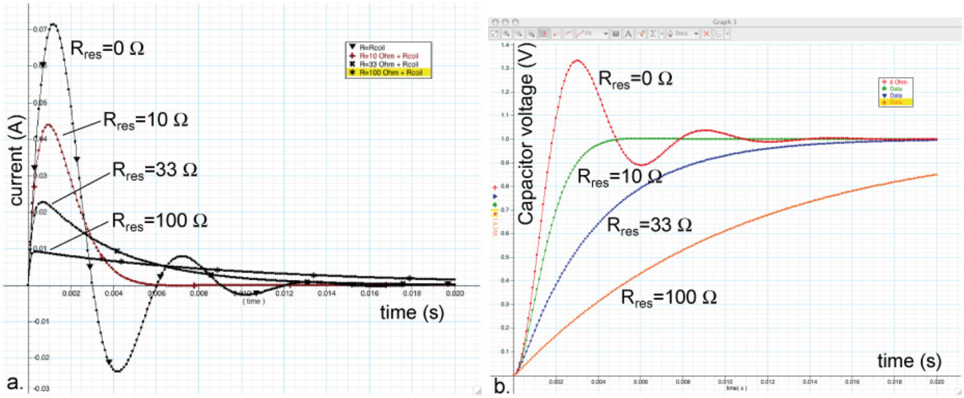


Figure 6: Experimental curves for the current (a) and the capacitor voltage (b) for different values of R_{res} (L=8.2 mH and C=100 µF). (Carstensen & Bernhard, 2009, p. 404)

For further description on the possible variation of the curves see appendix, and the lab tasks.

2.4 Intended links

Sometimes teachers discuss the connection between theory and practice in terms of applying mathematical theories on technical problems. According to Andrée Tiberghien (1998) “an important aspect of physics learning is to establish meaningful links between such pieces of knowledge”. It is not just an application of previous knowledge, or to learn links that are already there to learn, but an active learning process, which we explore in our research, and will define as *to make links*. Again looking at the model of the intended object of learning (Figure 2): The arrows in the figure illustrate the links that are intended for the students to make. Some of the links are between different mathematical models, e.g. obtaining the transfer function through the Laplace Transform, or calculating the inverse transform to obtain the time function. Other links are between objects in the ‘object-event’ world, e.g. carrying out measurements to obtain graphs. However some of the links are connecting the ‘object/event world’ to the ‘theory/model world’, e.g. deriving the differential equation from physical models or as in the lab studied to compare a calculated graph to a measured graph. Very often deriving the differential equation from physical models is taught in a physics course, where electric circuits is just a small part. Later it is expected that this is known by the students, although text books often give a revision of differential equations. On the other hand, Laplace transforms are often taught in the circuit theory course, or at least a thorough revision is provided. Going around the circumference of the circle seems to be a valid teaching strategy, although the circle has not appeared in any course literature or in teacher materials.

However, some of the expected links are instead across the circle. An expert in the area would be able to go directly from the Laplace-expression, the transfer function, to the calculated graph, or from the measured graph to the transfer function, and also set up the transfer function directly from the circuit, not by means of the equation. He would even possibly be talking about the differential equation, and yet give the expression of the transfer function.

The model can be used either for current or voltage, and very often the transfer function is given for the calculation of the output voltage. Also in the revised lab the suggested calculations to do as preparation, and the simulations done in the beginning of the lab are done for the voltage, although the calculations asked for in order to make the curve fit are for the current. Whether this is a problem or not will be discussed in the result, but here it is pointed out that the results of the calculations are rather similar:

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

$$u_{out}(t) = a - ae^{bt}\sin(ct + d)$$

and that teachers switch talking about current and voltage in a non-explicit manner.

That the students do not consider the measured and the calculated graph as the same, is found by research, but is implicitly shown by the intention in the lab – to make a curve fit between the measured and the calculated graph.

For the expert the concept transient response has merged into a whole, and he switches between the parts without noticing this. This is in terms of variation theory to keep the aspects of the phenomenon in focal awareness simultaneously (Marton & Booth, 1997). To learn about transient response is to learn both the parts – the concepts involved, the islands, and the whole – to make links between the islands, thus to keep more than one island in focal awareness at the same time. As well what the links are, as what it means to keep them in focal awareness simultaneously will be dealt with in the result and discussion.

2.5 A short review of how the text book used in the course presents the transient response

The differential equations are considered known from mathematics courses, and the Laplace transform is given a chapter of its own. In the text book (Nilsson & Riedel, 2001) the Laplace transform is presented as the mathematical tool it will be used as, thus the chapter is called “Introduction to the Laplace Transform” or something similar. The description includes the definition, transformation of functions and differential equations and the inverse transform. It also highlights a couple of mathematical tools necessary in the transformations: partial fractions and complex roots. The examples are varied systematically so that all different types of solutions are explored, i.e. all different types of fractions are varied, but when doing so the examples are rather complex, and values are not stemming from real circuits. No graphs are asked for. Some examples at the end of the chapter come from electric circuits, but they stop when a numerical answer is found. The examples go either from the time domain to the frequency domain or the other way, but never both directions for the same example.

The next chapter is focusing the use of the Laplace transform to perform circuit analysis: representation of components, step response, the transfer function, the steady-state response and the impulse response. The examples here try to exemplify all different kinds of situations in electric circuit analysis. The steps from the real circuit to the transfer function are often made directly, without giving the differential equation. No graphs are asked for except in the area of convolution, which is often not dealt with in a first year course. There is a conscious choice of examples where voltage and current are explicitly asked for in the same problem, thus highlighting the similarities and differences between them.

There are thus systematically varied examples in the book, but they are not varying the aspect that we found was critical, to show which graphs, and thus solutions to the inverse transform, that were possible. It is not just variation, but variation in critical aspects for learning that need to be explored.

3 Some philosophical inquiry on technological knowledge

Research on learning requires some discussion on what learning is, and specifically what learning of a subject might be. A reflection on technological knowledge could be such a groping attempt. To look for answers in the philosophy of the particular subject often helps in the search for what the knowledge of that subject and the learning of that subject may be (Williams, 1996).

This chapter will deal with two strains of philosophy of technology, namely what technological knowledge is, and what an engineer is.

3.1 Introduction

In the field of science and technology education the two – science and technology – are grouped together, a grouping which becomes as well a benefit as a problem. Since the field of technology education is relatively new, it is convenient to learn methods and use theories from science education. But on the other hand this also becomes problematic since technology and science are very different in their products, in their methods, in their epistemology, i.e. in their 'essence'. Very often they are discussed as were they congruous or interchangeable, or one of them just an application of the other.

Entering the science and technology education research from an engineering viewpoint, I did not even recognize what I would call technology in the discussions of technology in our seminars. What was it that I, as an engineer, saw in technology that was not part of my colleagues' views? Why did I not recognize their view of technology as technology? This made me turn to philosophy of technology and to a course which aimed at discussing what technology means, what new technology brings into our views of society, but also gave the opportunity to explore technology as knowledge, which is the least discussed aspect of philosophy of technology.

> "we shall be questioning concerning technology" (Heidegger, 1954/2003, p. 252)

A first question could be: "What is Technology?". A short and simple answer might be: "Technology is all the artefacts surrounding us". But technology is not as simple as that answer. Maybe, even the question itself is an impossible one to answer.

Some of the aspects of technology seem to be more obvious than others, deeming from the literature on technology: artefacts, skills, the cultural impact of technology, and often also the relation to science. Although all these aspects are recognized, they are not dealt with in the same manner, and since the picture will never become a complete "grand theory" the debate can go on without recognizing any "new" aspects. There is enough to discuss already as there is, so why bother to include questions on technology as knowledge? From my viewpoint there are important questions that originates from the questions about technology as knowledge, e.g. what is technological knowledge, what is engineering knowledge, what implications do such questions give onto technology and engineering education, what may they imply to research in education?

To settle with a philosophy of technology that includes only artefacts, skills and the relation to science is to prevent the engineer from recognizing his own enterprise, but also, and that is for me a bigger problem, hinders children and students to take interest in technology, and to hinder interest is to hinder learning. If a child already has an interest in technology, and does not recognize school-technology as technology, the interest may be completely lost. To open up the views of technology would perhaps make technology more interesting. This should, of course, not be seen as a wish for all children to choose technology, but at least make it possible for those who have that interest to see the opportunities given in engineering education and profession.

In this chapter I will make some reflections upon the question of technology as well through some historical as philosophical aspects. I will mostly discuss the aspect of technology as knowledge. In doing so, I am taking the risk of talking about questions that are not in the experience of the lifeworld of some of my readers, which may cause the reader to put away my thoughts as stemming from a platonic view, although I claim that my discussion is in the phenomenological tradition. I may sometimes use words that seem to come from a dualist world-view, but if so, that is a reminiscence of the language of scientists and technologists in unreflected daily use of the words. Many other attempts by technologists to address the question of technology as knowledge have been dismissed due to a dualist language, when they could have been taken up by phenomenologists as examples to start looking for the structure and ordering that is part of the phenomenological tradition.

I will use an example from school technology as a point of departure. What roles does Technology play, as well as an enterprise of its own, as in relation to science? A special focus will be given to how poor the reasoning about technology becomes when only artefacts and skills are discussed. Even the focus on science and technology, which has been vividly debated, makes the question of technology as knowledge superficial. It puts the focus on a question that seems important, but since the answer always becomes – it is not the same, they are different - it appears as if the question of technology as knowledge has been responded to, and further investigation is dropped. It is at this point that the question really arises. When philosophy reaches a horizon, it seems to me very strange to stop the questioning; rather, seemingly reaching the horizon ought to imply the opening up of the next question, and thus a new horizon to reach out for. The focus here will thus be on how to go on questioning about technology as knowledge, and not to stop at the point where it invites to further investigation.

I will also discuss what implications this may pose on theories of educational research, as well for science education as engineering education.

Let us start the journey by looking upon a task from the technology classroom in schools:

“Build a Foot Pedal Trash Bin”

3.2 “Foot Pedal Trash Bin” – an example

A foot pedal trash bin can be made from rather regular materials, and is easy to make function. It can be sufficient to use some ice cream sticks, some nails or clamps, cardboard for the lid and bottom, and cylinder, glue and scotch tape. The levers that are used are rather easily comprehended, at least if one has seen a lever at work.

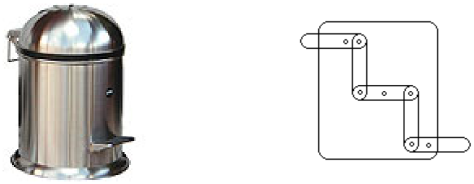


Figure 7: The foot pedal bin a) the real design b) the model of the design

What is the technology in this example (cf. Figure 7)? Let me anticipate some issues which we will return back to later in the philosophical discussion.

The picture illustrates two ways of seeing the knowledge aspect of technology, the first the aesthetic design, the other the functional design. For both of them the word “design” is used. In some other languages “design” is only used for the aesthetic aspect. In Swedish the word “design” is usually referring to the aesthetic aspect, also when it is translated into the word “konst”. But the word “konst” would in the most direct translation into English be the word “art”, which may refer to both arts and skills. The parallel use can be exemplified by “konstgjord and “artificial”. Etymologically the word “konst” means skill, also in the sense of acrobatic skills, but is also related to the word for strange (konstig).

The example also illustrates that by technical activity we usually have a product as the goal for the activity, and that the most convenient way to learn to produce a well-known product is through an apprenticeship toward the one who already can build this mechanism.

The children enjoy the task, and when they get it to work they are very satisfied. Some of them also enjoy making something they feel is useful.

But if, in the technology education, the production of the artefact is all there is, the attitude changes[3] (Skogh, 2001, p. 168). Ending by the object and the activity, the Technology[4] lacks, the knowledge that makes technological development[5] possible, the knowledge that is the expert competence stemming from engineering education and professional experience. In the example above this knowledge could be recognized in the classroom by asking the children: “What more do you think this lever-mechanism could be used for?” By letting the children use their imagination they become curious again, something that for Dewey is a prerequisite for learning. Technology can become fun again. Many teachers already do this of course, and the curiosity is maintained, or even enlarged, but sometimes due to lack of time or other

---

[3] Cf. also the discussion in chapter 3.5

[4] Capital T is used in the manner that Espinas introduced (cf. next section)

[5] By development I don’t mean towards an ultimate end, but in the everyday meaning to make new products, which I believe is not only an act of skill but also another kind of knowledge, which I will come back to later.

circumstances, they stop ”when it is the most fun”. To ask for what a technology may be used for, more than in the actual application, is to go on with Technology.

What technology is, how it is developed, apparent from the technologist’s viewpoint, but not always to the historian or philosopher, will be discussed below. The questioning will take on a phenomenological view where the answer to the first question “What is technology?” is an impossible question, but one that can be rephrased in several ways. The reason for keeping the original question, or rather to be aware of the original question is that the question still is the everyday way to pose the question. In the discussion we will come back to the example above from some different angles.

3.3 technics, techniques, technology and Technology – Some philosophical starting-points

One way to define technology is to use the French social theorist Alfred Espinas’ idea of “techniques (skills of some particular activity), technologie (systematic organization of some technique) and Technologie (generalized principles of action that would apply in many cases).”(Mitcham, 1994, p. 33) Another way to categorize technology is as the tools man creates to project his body, e.g. the spade as a projection of hands and feet, (Ernst Kapp cited in Mitcham, 1994, pp. 23-24) and the skills man develops in order to handle the tools, e.g. how to dig, or something more skilful, the craftsman’s skill, e.g. the carpenters skill. These two categories are explored by most of the philosophers mentioned in Carl Mitcham’s book “Thinking through Technology” (Mitcham, 1994). The knowledge of technology is more than skill, but is rarely explored. Using Espinas’ categories may be of help here: technology (note the lower-case t) could be to organize skills into systems used for production of new artefacts, maybe what Bunge calls “rules of thumb”(in Mitcham, 1994, p. 193) and Technology (upper-case T) technological theories, generalizations proven by evidence through scientific research, used as general methods.

Further explored by Mitcham, he proposes a figure:

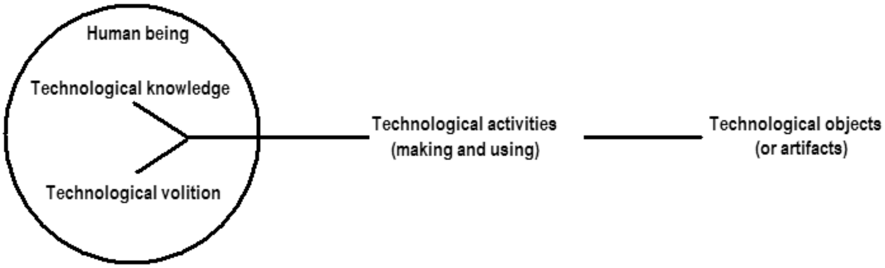


Figure 8: Modes of manifestation of technology (Mitcham, 1994, p. 160)

Mitcham uses this figure as an instrument to analyze different aspects of technology, so as to make it possible to analyze them separately and in relation to each other. After an exposition on different categorizations, he wants to “propose and develop a typology that can encourage an active dialogue with such previous attempts, protecting and ordering the insights they contain.” (Mitcham, 1994, p. 157) Although there are no arrows marking intentionality (as defined by phenomenologists)[6], Mitcham expresses what could be interpreted as the intentionality in philosophy of technology: “Technology as activity is that pivotal event in which knowledge and volition unite to bring artefacts into existence or to use them; it is likewise the occasion for artefacts themselves to influence the mind and will.” (Mitcham, 1994, p. 209)

Can it be that the intentionality makes the focus of philosophical inquiry be the artefact or at the most the activity, and that inquiry about knowledge and volition comes into background? Or is it as Dewey suggests that technology is an “active productive inquiry” (Hickman, 1990, p. 23), “an activity of doing and making” (Dewey, 1938, cited in Hickman, 1990, p. 27)? We will come back to this question and discuss the closing that results from neglecting knowledge when discussing technology, and the opening that the functional view may imply. But first a brief overview of aspects discussed in “Thinking through technology” (Mitcham, 1994).

Technology as object

To view technology as object, man-made artefacts, is the most obvious category. It is discussed in all texts concerning technology, and is discussed regardless of educational background. Technology as object is also the aspect that philosophers and historians have commented on. One question has been whether or not animals produce technical artefacts, another how artefacts should be categorized: according to use, e.g. as tools, utensils, machines or according to physical principal, e.g. inclined plane, lever, scales. Often the objects are seen as extensions or amplifications of the human body. Another way to view them is as transformation of energy. In relation to this has also “the inherent will” of the artefact, technological determinism, and other similar questions been raised.

Technology as activity

Viewing technology as activity, Mitcham distinguishes bricolage from engineering. He also discusses how systematical the process of development may be, whether the process could be applicable to other areas than where it first was applied. The words techniques and technologies are also explored. In as well French as German the word technics is used for skills and technologies for the practical aspect of technological knowledge, while in English the word technologies is used to represent as well production as use of artefacts. Another difference could be that technologies always include rules, whereas techniques could contain nonrational components (Mitcham, 1994, especially pp. 235-236). The chapter about technology as activity is a rather lengthy one, which could imply a question of whether technology as activity is a possible category of inquiry. In science education Andrée Tiberghien (2000) has proposed that the divide should not be between theoretical and practical knowledge but rather distinguish knowledge of the theory/model world as opposed

---

[6] Intentionality is here the view that “every experience has its reference or direction towards what is experienced, and contrarily, every experienced phenomenon refers to or reflects a mode of experience to which it is present.”(Ihde, 1986, pp. 42-43)

to the object/event world, since both worlds include as well procedural as conceptual knowledge. An indication that this may be a more useful categorization is that technology as activity is dealt with in more than one category in Mitcham's book, especially it comes back in relation to technology as knowledge.

If on the other hand technology *is* activity, as Dewey views it, then technology as activity is not a category, it is the definition (Hickman, 1990, p. 1)[7]. We will come back also to this in the part "towards a philosophy of technology".

Technology as volition

The fourth of Mitcham's categories is "Technology as volition". Questions asked here are: Is there an inherent will of technical objects? Is technology deterministic towards catastrophe? Is technology "evil", "good" or "neutral"? The reason to pose the question is that all technologies can and will be used for other purposes than they were first designed for. Some philosophers claim that every technology carries its own catastrophe. Heidegger, Borgmann, Ihde, and others give warnings about the risks, but claim that the evil is not inherent in the technology itself, but that the risk is to view the technology as the essence of being (Heidegger, 1954/2003, p. 261), forget the important matters of life (Borgmann, 1984/2003) or let the amplification, which instruments can give, become so interesting that the reduction of sight is not acknowledged (Ihde, 1979 discussed in Mitcham, 1994, pp. 188-190) or to view technology as neutral (Ihde, 1979/2003).

Heidegger claims that the danger does not lie in technology itself, but in the risk man takes when he tries to order his life by mathematical rules for everything.

> "But enframing does not simply endanger man in his relationship to himself and to everything that is. As a destining, it banishes man into the kind of revealing that is an ordering. Where this ordering holds sway, it drives out every other possibility of revealing. Above all, enframing conceals that revealing which, in the sense of poiésis, lets what presences come forth into appearance. As compared with that other revealing, the setting-upon that challenges forth thrusts man into a relation to whatever is that is at once antithetical and rigorously ordered. Where enframing holds sway, regulating and securing of the standing-reserve mark all revealing. They no longer even let their own fundamental characteristic appear, namely the revealing as such." (Heidegger, 1954/2003, p. 261)

Let me give a recent example of technology that developed in an unexpected way, without giving negative consequences (at least yet). In the local newspaper of my city one could recently read: "Vibrating road marks give safer roads" (Arnroth, 2000). The article explains how the road marks have been developed. The marks in the middle of a road was first painted

---

[7] According to Hickman Dewey has a philosophy of technology, but instead of explaining technology, Dewey uses technology as the metaphor for e.g. knowledge, calls language a technological artifact, etc. Dewey's way of using technology, and referring many other activities in the lifeworld as technological or technological artefacts shows that for Dewey technology was a tool which he used in his inquiry into other philosophical questions, but also that "'technology' became a synonym for his [Dewey's] very method of inquiry" (Hickman, 1990, p. 1)

only in curves, to avoid accidents. After some time there were marks following the whole path as well in the middle of the road as along the sides. During the 1960's these were covered with a thin layer of a reflective surface. The reflective material deteriorated rapidly by ploughing snow in the wintertime, and a new way to paint was developed: Instead of a solid line, it was divided into short marks across the intended line, but not to make these tear up too rapidly a solid line was painted parallel to it; the line was called a "comb-line". The line was now not easier to see in rainy weather, but it had an "unwanted" side-effect: It gave an irritating sound. Soon it was found that the sound from the vibrations was primarily what made the drivers react on the marks, and not the visual effect. The innovative development is now to make this sound-signal even better by making prints in the asphalt-coating, so that even when the reflective line is gone, there is a sound. The sound was a better warning to the car drivers than was the light-marking that was the intended technology. The development was driven by economical reasons, as much technological development, but resulted in a different safer technology, one that was not anticipated, or even possible to predict. In the discussions of philosophy of technology this "positive volition" hardly ever is mentioned, only the negative, determinism is normally discussed.

Technology as knowledge

Technology as knowledge[8] has according to Mitcham also been considered in inquiry about technology for a long time. Historically the divide has been that technological knowledge has dealt with the artefacts, and that this knowledge has been different from the knowledge about the nature. The maybe most argued difference has been that scientific theories are generalizations, where the aim is to find one general theory, whereas technology is to apply science in order to create artefacts. The aspect of technology which is thus not considered, or rather just overlooked, is technological theories. Mitcham instead categorizes technology as knowledge in four subgroups (Mitcham, 1994, pp. 193-194):

1) Sensorimotor skills or technemes
2) Technical maxims, rules of thumb or recipes
3) Descriptive laws or technological rules
4) Technological theories, divided into substantive and operative

Skills are here recurring. Whether skills, "techniques" are to be categorized as part of knowledge or as activity is debated by several philosophers. Again I repeat my question: If something appears in more than one category, maybe there is something wrong with the category? Could it be that "skills" is not a category of its own right, but part of all kinds of knowledge as well as of activity? Or is "skills" the category and activity the ambiguous one? Let us come back to this question later. Those who see skills as knowledge often discriminate

---

[8] The question I first asked was: "What is technology?", may of course be dealt with from all four perspectives Mitcham deals with, but the one closest to what I was dissatisfied with in the reasoning about technology, was what Espina (Mitcham, 1994, p. 33) calls Technology (upper-case T), and what Mitcham here calls "technological theories" (Mitcham, 1994, p. 192 ff.). I will deal with this somewhat more than the other aspects, and also try to give an alternative view of technology as knowledge.

a cognitive from a practical dimension. Both of these are tacit, non-discursive (Mitcham, 1994, p. 196), but are to e.g. Michael Polanyi and Gille knowledge, since they are acquired through teaching, even if this teaching is not outspoken, but through apprenticeship. Philosophers that argue that skills are not knowledge but only activity, think of knowledge solely as the kind of knowledge that can be expressed by words.[9]

Many philosophers distinguish between technics and technology, where technics are the practical skills and technology is the theoretical. Mainly they are found among the scientists and technologists. One of them is Mario Bunge, who first divides practical knowledge into technics (craft skills), technical practice (engineering practice, medical therapy, etc.), and pseudotechnology, but also divides technology into rules and theories. He argues that technology is applied science, but whereas scientific knowledge consists of "observations, laws and theories", technological knowledge consists of "actions, rules and theories" (Mitcham, 1994, p. 197). Technics and engineering rely on technology, and use scientific knowledge to create artefacts. A key question for Bunge becomes to investigate the relation of technology and science.

Relations between science and technology

It is easy to make the question of the relation between science and technology a dominant issue, and thus "get stuck"[10] in that discussion, instead of continuing the questioning on technology as knowledge. I will therefore here make this an issue of its own, but only make some remarks that for me is sufficient as argument for dealing with technology as a separate issue. I will only mention some issues that make a path into the question of technology as knowledge.

One view of the relation between science and technology is that science tries to explain all phenomena through a few theories, reductionism, (Sjøberg, 2000, p. 63) and technology aims to create many products out of these few theories. This view is impossible for an engineer. There are theories in technology that have nothing to do with science and still can be seen as reductions too, e.g. theories in control theory or theories for computer programming. Bunge's categorization into rules and theories, and especially his division of theories into substantive and operative theories, deals with this. Substantive theories are those that are close to scientific, e.g. thermodynamics, and operative are those that are found by scientific methods but are not dealing with natural phenomena, e.g. operational research and he claims that scientific theories describe natural phenomena, and that they may be more or less ”true”, while technological theories are prescriptive and are more or less effective (Mitcham, 1994, p. 197). The difference then reduces to the starting point for the study, for science to get to know nature and for technology to control it. For Skolimowski (1968, p. 554, italics in original) it is precisely that "science concerns itself with what *is*; technology with what *is to be*" , that makes technology something different from science.

---

[9] "within the domain of skill … there is no transformation … to abstract or formal and therefore conceptually teachable knowledge", (Mitcham, 1994, p. 196)

[10] Cf. p. xi in the introduction to Hickman (1990)

Others, mostly sociologists and historians who have used technology as object of study, point to parts of technology, which cannot be explained by science, such as what drives the development.

Usually scientists accept the falsification Popper introduced, i.e. when a theory is tested and one single test proves the theory to be false it should be abandoned. Thus it becomes very strange to continue to claim that technology is applied science. Particularly problematic is to speak of old technology as applied science, since the applications are developed before the scientific discoveries are made. One possible reason for the view may be that scientists want to view their enterprise as a more sophisticated one than they consider technology, and that this becomes strange to the technologist. It can also be viewed as an attempt by scientists to understand technology, but since it obscures technology itself, the discussion becomes tempting for both scientists and technologists.

Some problematic examples from history of science and technology

> "Science and technology, research and development – these are assumed to be almost inseparable twins. They rank among the sacred phrases of our time." (McClellan & Dorn, 1999, p. 1)

Although McClellan and Dorn start their textbook for undergraduate students by marking that this is a non-historical statement (this intimate correlation assumed between science and technology is rather new to the 20th century) they have problems describing the development of technology. They do describe the development of scientific knowledge, and they give an extensive history of technical devices, but not the development of technological knowledge.

That science and technology have developed separately, and only met contingently, is made very clear in many books on the history of science and technology. As well McClellan and Dorn (1999), Lindqvist (1989), and Hansson (2002), as other historians of technology establish that not until the 18th century, and "the scientific revolution" (McClellan & Dorn, 1999, p. 293) there was any questioning about whether there is any differences between since and technology or whether technology at all could be counted as a science. Lindqvist (1989) writes that it was not until the 16th century that technics became technology[11]. Reading Mitcham (1994, pp. 128-131), this seems at a first glance to be wrong, but reading closely, "*technologia*" is only used for rhetorics in the ancient Greek texts, and appears as technology first during the 16th century. On the other hand Aristotle does not discuss scientific knowledge, but considers the knowledge of producing artefacts and art as a knowledge of its own right, *techné*, and *episteme*, the closest to science , as only contemplated knowledge (in the new English translation) *episteme* is translated with science, although the translators also discuss the ahistorical use of the term.

The use of technology for technological knowledge would thus coincide with Lindkvist's idea since the Swedish development in those days was delayed by about 100 years compared to the English history. At this time institutes for systematic research and collaboration were

---

[11] "att den största tekniska förändringen under 1700-talet var att 'teknik blev teknologi'" (Lindqvist, 1989, p. 121)

founded; in England the Royal Society was founded in 1660 and in Sweden the Royal Academy of Science (Kungl. Vetenskapsakademin) was founded in 1739 and Swedish Steel Producers' Association (Jernkontoret) in 1747. They were often sponsored by the governments, but were independent and promoted the freedom of science. They organized the knowledge, spread it through books and journals, and later also started schools for higher education in technology. Already in a speech in the Academy 1764, Torbern Bergman talked about the importance of using scientific methods and discoveries.[12] However, not until the 19th century the new technologies, dependent on science, appeared, e.g. paint-industry depending on chemistry, telegraphing depending on the discovery of induction. But according to McClellan and Dorn, technology is still developed with little connection to contemporary science:

> "Even though the telegraph tapped a body of preexisting scientific knowledge, the development of the new technology of telegraphy involved the solution of a myriad of problems – technical, commercial, and social – that had little or nothing to do with contemporary scientific research or theory." (McClellan & Dorn, 1999, p. 309)

Unfortunately McClellan and Dorn do not discuss how these technological discoveries are made. They settle for the history of science. They neither discuss whether science is used in technological development nor do they discuss the development of technological knowledge or methods. However they mention technological inventions, such as the electric bulb by Edison, they consider all these inventions as results from "trial and error", without any preceding explicit idea of what may come out of the experiments[13]. But, they do point to the necessity of technological development to be at hand before a specific object can be discovered, again the example of Edison:

> "a large and complex technological system had to be brought into being before the electric lighting industry could be said to have existed" (McClellan & Dorn, 1999, p. 310)

In a historical description it would be interesting not only to follow the objects of inventions, but also the knowledge.

Of course the artefacts are the obvious historical evidence, and knowledge usually is communicated by texts, the history of knowledge has to rely on those documents that are kept. Since the products of science have always been texts, and the products of technology have

---

[12] ”Vetenskapen bör hjelpa oss, at använda Naturens alster til vår fördel, och at tillfredsställa våra förnödenheter, så hafva de tillbaka at vänta vederbörlig heder, omvårdnad och belöning; men innan de med framgång kunna tjäna, behöfva de en viss högd eller grad av fullkomlighet, hvilken är att ärnå, de böra skyddas och uphjelpas i afseende på det, som de i framtiden lofva." cited by (Lindqvist, 1989, p. 179)

[13] "trial and error" without systematic scientific research for a solution to technical problems is a recurrent theme in McClellan and Dorn (1999) when they describe technology. See e.g. p. 280 ("tinkering"), 281, 310, 312 ("'research' often still took the form of trial and error") or p. 200: "developed independently of any theoretical concepts". Also they use words as "intuition and experience of craftsmen" e.g. p. 174, 200, 268, 287, 292. On the contrary science is described as systematic and thorough, see e.g. p. 305 ("in this way the Classical World View incorporated the tradition of the classical sciences initiated by Newton and perfected by two centuries of problem-solving research", p. 326 ("the pieces fell into place with a regularity and precision that transformed theory into accepted fact").

been artefacts, this becomes an imbalance. In texts it is possible to follow as well revolutionary, paradigmatic and sudden shifts as the more gradual development. McClellan and Dorn e.g. talk about early scientific development as “the rise of science as rational debate” (McClellan & Dorn, 1999, p. 61). But as much as they notice the scientific development through the saved texts, they fail to even discuss the possibility of technological development, probably because the gradual development is not so obvious in artefacts as the sudden innovations, and is not documented in texts.

Gies and Gies (1994), who have rewritten the historical development of technology during a specific period of time, namely the middle ages, have on the contrary described the more continuous development, i.e. the development between sudden shifts, which has led to a total reformation of the view of the middle ages. This time was formerly described as “The Dark Ages”, a period of stagnation, which it would be if “only” inventions and new theories were considered. In their book the middle ages instead becomes an era dominated by significant development. During this period development is evident in many areas: cathedrals are built, waterwheels are optimized for different purposes, agricultural tools are developed, and the trade, especially with China is increasing.

Interestingly McClellan and Dorn praise the rationality of science and its search for the one and only theory, while they do not at all give any accounts to the technological development, even though they have pointed out also the problems science has had with problematic theories. In addition to this they also favour the European (including the North American) science. One example is where an ancient view is accepted as science when it is described by the Greek Thales, but when almost the same idea comes from China it is not at all scientific. The wonderings of Thales about water and fire are described as:

> “the first attempt to say something about the material 'stuff' making up the world around us. It marks the beginning of matter theory” (McClellan & Dorn, 1999, p. 61)

But the Chinese theories building upon yin and yang, but in principal present the same elements as the Greeks: metal, tree, water, fire and earth, they write:

> “nothing united these separate endeavours into a distinct enterprise of critical inquiry to nature”

and

> “the Western concept of science or natural philosophy remained foreign to intellectual thought in traditional China” (McClellan & Dorn, 1999, p. 127)

They also claim that one should not try to describe who discovered something first, since

> “Such claims reflect a perverse judgementalism and a desire, in the name of multicultural relativism, to inflate the accomplishments of Chinese science while devaluing those of the West.” (McClellan & Dorn, 1999, p. 128)

Aren't McClellan and Dorn here doing exactly the mistake they are cautious about, namely to place one culture before another? Why would the Chinese have had a desire to build a science on the old Greeks? Interestingly the Chinese had an "explanation" on magnetism that preceded the invention of the compass, e.g. the same order of discovery as science and technology in Europe in the 19th century. Although described in their own book, it does not seem that McClellan and Dorn admit this, since that would punctuate their theory that technology always preceded science until the scientific revolution. Instead they just state that the development of the compass was not a direct consequence of the "scientific" explanation of magnetism.

No, the description of European science and technology as a rational endeavour and technology as a series of *ad hoc*-solutions becomes problematic, and especially problematic it becomes when the same person contributes with discoveries of both kinds. Thus McClellan and Dorn choose to let Archimedes be "only" technician (he was called an *architecton,* see the chapter on the word engineer below), and describe him in much more inexplicit terms than when they describe scientists:

> "Archimedes probably did apply himself … . He supposedly used his knowledge…he acted as an engineer…" (McClellan & Dorn, 1999, p. 87, my emphasis)

They do not even mention Leonardo da Vinci, who made very extensive research on e.g. the movements of water, how sediments were transported, and used this as knowledge when constructing water canals. Most of Leonardo da Vinci's notes are in the form of pictures, and many dealt with construction, but as well his studies of the human body as the movement of water, necessarily have to be considered systematic and scientific, since he first claims a theory for his investigation, then documents his experiments, although the documentation consists more of pictures than of text. Leonardo da Vinci is also the first to use arrows to model forces as both value and direction, an early form of vectors. This model is still used in mechanics today. That Leonardo is an autodidact can not be sufficient to discard him as a scientist, nor a technician.

If science is to search for "one theory", science is not older than the "second scientific revolution". Before that there is no search for the one and only theory (McClellan & Dorn, 1999, p. 299). Has technology ever had that kind of aim? It can also be questioned whether such a claim is possible even in science today? Who would want such a theory? Is the search for the grand theory just a myth?

What then are the relations? How to avoid the ditches: applied science or total ignorance of any relations?

In the introduction to the book "The Nature of Technological Knowledge" Laudan (1984) discusses the possible reasons for the neglect to study the development of technological knowledge, the development between the paradigmatic shifts. She provides three main reasons to why development of technology as knowledge has been neglected or misinterpreted:

1) “the assumption that technology is quintessentially tacit”
2) “the identification of technological knowledge with applied science”
3) “the selection of analytical units for the history and present structure of technology that, however useful for some purposes, do little to throw the cognitive aspect of technology into prominence”. (Laudan, 1984, p. 6)

A reaction to the debate in the 1980’s was that historians tried to see technology as something different from ”just” applied science, and maybe the book by McClellan and Dorn is a result from that debate. It shows however how difficult the task to find the history of technology through the inventions is. According to Laudan: “in light of the struggle to see technology as more than simply applied science, this emphasis has blocked any attempt to exploit the possible parallels with science.”(Laudan, 1984, p. 11) To consider technology as “tacit knowledge” has also made historians relinquished from research in the development of technological knowledge. Some of the noticed problems are:

> “such [technological] knowledge is rarely articulated, and since when articulated, such knowledge is largely in visual rather than verbal and mathematical form it does not lend itself to analysis by a scholarly community trained primarily in the analysis of texts and the explication of logical structures.” (Laudan, 1984, p. 6)

In the symposium, from which the book is a result, the participants admitted that although technology includes a certain amount of “tacit knowledge”, it is possible to investigate the “cognitive structure” of technology. (Laudan, 1984, p. 16)

Bunge’s view that the technological theories are similar to the scientific, since they confine to the same methods, but that they have different purposes – knowing the world and controlling the world respectively (Mitcham, 1994, pp. 197-198) – is one way to approach the relation between science and technology and still admit the relevance of study of technological knowledge development. Boel Berner, a Swedish scholar in sociology of technology claims that it is essential to consider the different aims of the enterprises in order to study the development of knowledge they result in:

> “Scientists live in an environment where they want to know how nature …*is* and where one tries to find theories that explain different phenomena deeper and more truly than former theories. The goal is knowledge and only indirectly, if at all, practical benefit. Technicians and engineers do the opposite: They search for knowledge, e.g. through experiments, to be able to act. …
>
> The *aim* is thus the difference, which leads to different *ways of working* and a different view of what can be respectively accepted as a scientific or technological *result*.” (Berner, 1999, p. 55)[14]

---

[14] My translation. ”Naturvetenskapliga forskare lever i en miljö där man vill veta hur naturen … *är* och där man söker komma fram till teorier som förklarar olika fenomen djupare och sannare än tidigare teorier. Målet är ökad

In his exploration of "Technology is much *more* than just applied science" Sjøberg (2000, p. 76, italics in original)[15], professor in science education in Oslo, tables some characteristics:

Science	**Technology**
Explain, understand, motivate. "Know why"	Solve practical problems, handle actual situations. "Know how"
Product: ideas and concepts	Products: Substantial objects, pieces of art, things
The general: Concepts, ideas, laws and theories	The specific: The unique, the specific situation
Theoretical and abstract	Practical and concrete
Clean and disciplinary	Applied and crosses disciplines (also into domains as economics, psychology and sociology)
Source of power: Research, Universities	Source of power: Industry, working life
Free, open, accessible, universal	Expensive, patents, licenses, secrets
Strives at being first to make knowledge known to others	Strives to keep knowledge secret

Table 2: One comparation between Science and technology suggested by (Sjøberg, 2000, p. 82)

But although Sjöberg views technology as something more than applied science he does not discuss what technological knowledge is any further.

One way to view the relation between science and technology is the use of technology in scientific research. The use of new technological instruments has very often been the reason for paradigm shifts. The new instruments have opened up for new views, made us aware of things that were taken-for-granted. For Gallileo the telescope made it possible to see stars and planets in a new way, through the microscope it was possible to see what caused diseases, and so on. This is what Ihde calls "instrumental realism" (Ihde, 1991). By this view it is possible to respond to the question "who applies who", but not the question dealing with similarities and differences in methods to acquire new knowledge.

---

kunskap och endast indirekt, om alls, praktisk nytta. Tekniker och ingenjörer däremot gör tvärtom: de söker kunskap, t.ex. genom experiment, för att kunna handla. …
Syftet bakom arbetet skiljer sig alltså åt, vilket ger olika *arbetssätt* och olika syn på vad som utgör ett naturvetenskapligt respektive ett tekniskt tillfredsställande *resultat*." (Berner, 1999, p. 55)

[15] "Teknologi är något mycket *mer* än bara tillämpad naturvetenskap". (Sjøberg, 2000, p. 76 italics in original)

There are also some characteristics of technology that are overlooked, when the knowledge is only compared to scientific knowledge. Engineers often have to deal with ”problematic data”, e.g. measurements made on a small scale model, where there is no evidence that the full scale object will behave in the same way as the model (Edwin Layton, 1976, in Mitcham, 1994, p. 202). Very often simplifications are made from practical experience, although there is no way to warrant the conditions for the reliability of the model. Walter Vincenti uses as his examples the design of the airplane-wing, and the turbulent flow at the propeller, which yet is not physically fully understood, but still can be designed. He also tries to separate technology from science by giving account to other aspects of technological knowledge which not necessarily come from science, such as the use of handbooks, blockdiagrams or analogies. His categories of technology are: fundamental design concepts, criteria and specifications, theoretical tools, quantitative data, practical considerations, and design instrumentalities (Vincenti, 1990, p. 208). He also discusses the development of technology as knowledge in terms of: transfer from science, invention, theoretical engineering research, experimental engineering research, design practice, production and direct trial (Vincenti, 1990, p. 229).

According to Vincenti there are often technical problems that rise questions that science would never bother with, or at least consider uninteresting, problems that often render non-scientific solutions (Mitcham, 1994, p. 200).

Proponents of “The new scientific philosophy”, Thomas Kuhn and others, question whether there are any “strictly objective facts or observations that can uniquely determine some scientific law”, thus the question becomes: is science itself is so systematic as to make a foundation for technology (Mitcham, 1994, p. 204).

Heidegger comments on the relation between science and technology, and states: “Because the essence of modern technology lies in the enframing, modern technology must employ exact physical science. Through its doing so, the deceptive appearance arises that modern technology is applied science. This illusion can maintain itself precisely insofar as neither the essential provenance of modern science nor indeed the essence of modern technology is adequately sought in our questioning.” (Heidegger, 1954/2003, p. 259) He notices that technology is older than science, but that modern technology relies on scientific methods and results. They are interdependent but neither is a part of the other, and they need to be questioned separately.

Technology as revealing and poiesis

Heidegger is one of very few philosophers who gives account for all of the above aspects, and makes the philosophy of technology a whole, when he inquires about the essence of technology. He talks about e.g. the craftsman’s skill, the relation between techné and epistémé, and technology as a form of art:

> “We are questioning concerning technology, and we have arrived now at *aléthia*, at revealing. … Technology is a way of revealing. … We must observe two things with respect to the meaning of [*techné*]. One is that *techné* is the name not only for the

> activities and skills of the craftsman but also for the arts of the mind and the fine arts. Techné belongs to bringing-forth, to *poiésis*; it is something poetic.
>
> The other thing we should observe is […that] the word *techné* is linked with the word *epistémé*. Both are terms for knowing in the widest sense. They mean to be entirely at home in something, to understand and be expert in it." (Heidegger, 1954/2003, p. 255)

Heidegger here discusses technology as a creation, as well of objects as of theories. He talks of nature as something that reveals itself, while the artefacts reveal themselves through technology. His view that the question on the relation between science and technology obscures the essence of technology and that technology is a revealing, is a note that can also be applied to views of other areas of knowledge.

We will come back to what implications this gives to the philosophy of technology and also education.

3.4 What is an engineer?

To illustrate how technology as knowledge has been and is viewed in different cultures, one can follow the history of the word engineer.

Some of the professions that education in technology can lead to are technician, engineer and architect. Technicians are those who apply known technology to new products, while engineers are those who develop new technological theories (Mitcham, 1994, p. 148).

Architect is probably the oldest term for the designer of technical objects. The origin of the word is "Greek *architekton,* from *archi* (primary or master) plus *tekton* (carpenter or builder)" (Mitcham, 1994, p. 145). However, the word was not only used for the one who designed buildings, but also planned cities, water supplies, sanitation systems etc., i.e. what in English today is called *civil engineer*. One of the first to be called *architekton* was Archimedes (McClellan & Dorn, 1999, p. 87).

Mitcham (1994, pp. 144-149) reviews the etymology of the word. He states that there are two different backgrounds to the word: *ingenero* and *ingeniator*, where the first means generate, to produce, as well artificial as innate. The second word was used for the builders and operators of "engines of war". The English word engineer came to be used for the person who operated the engines. John Smeaton was the first to call himself (from 1768) a "*civil engineer*". This term is today in many countries used as a collective term for all engineers with a university education, whereas in English only those who are in construction engineering, i.e. those who in ancient times were called *architekton*.

The second meaning*, ingeniator*, was mostly used by middle age builders of cathedrals and castles. According to Garrison the origin of the word engineer is the word *ingenious*. In this sense it is used in the French term *ingénieur* (Garrison, 1991, p. 130) which came into use during the 18th century. In the 14th century there was a distinction between *de ingeneis* who planned and ordered the military forces and *de machinis* (Garrison, 1991, p. 120)[16] who operated the military "machinery", e.g. catapults and trebuchets.

As well ingenero as ingeniator come from Latin *gene*, which means origin and birth. The evolution of the words starts similarly, and the roots are:

> "genial, genius; congenial, from Latin *genius,* procreative divinity, inborn tutelary spirit, innate quality;"
>
> "engine, ingenious, from Latin *ingenium,* inborn character" (Indo-European roots, 2003)

The engine generates movement, and the genius generates thoughts. What does this imply for the engineer? Is he the one who operates the machine that moves by itself, or is he the person who generates new thoughts?

Even if the etymology is the same, the usage has diverged, and when the usage of the title engineer comes into use, the French and English terms do not mean the same. The word in English has been used for the more practically working engineers (sometimes called blue-collar engineers) and the French word has been used for the engineers from universities (but also later for the English white-collar engineers). The traditions in different countries are still today making the understanding of what an engineer is, a question of debate. As well the discussions about technology as knowledge, as the debate on what engineering education should include, how close to research or industry it ought to be etc. have their roots in the different meanings of the word engineer.

Hansson (2002, p. 402) writes: "In England there was an attitude toward the academic that was almost condescending" The person who had practical skills was praised, but the one from university was unskilled and good for nothing. This led to a rapid growth of industry, but when the technological development required academic research, Germany and France took the lead.

Another cultural difference that has had impact of the academy as well as the engineering profession is freedom of religion. In England the dissenters, those who did not want to belong to the state church, were not allowed to enter the universities. They therefore started their own schools for technology and economics studies. Furthermore, they were not allowed to work in governments or other authorities, which made industry their only chance to a career (Hansson, 2002, p. 277). This split in the society has most likely also affected the relation (or rather the divide) between science and technology in Britain, but also engineering as something apart from academic knowledge.

In Sweden there is for example a never-ending debate about engineering education. Engineers claim that science and mathematics need to be integrated into the applied subjects, while teachers coming from university sciences claim their responsibility to give the students a good academic base. This is also mirrored in the instruction from Högskoleverket (Swedish

---

[16] Terms used by Marianus Jacobus (1382-1453)

national agency for higher education), where the directives state that mathematics ought to be integrated into the courses where it is applied, at the same time as the evaluation, made by the same authority, criticises the universities who have done accordingly, by assessing the quality by counting the credits given in mathematics courses separately. This conflict between academy and practical technology probably stems from the different cultural backgrounds these teachers come from, but also the insecurity about what technology as knowledge is. If the national agency is going to be able to give an unambiguous directive, it is not possible to do as they do today, namely, that the group that are to assess the quality itself sets up its own rules for the assessment, but they have to find out what an engineer is, what an engineer needs to know, what technology is, and what technology as knowledge is. If this is possible at all, it has to be carried out as a philosophical and historical investigation that can bring forth the technological knowledge as well as open up for studies on what engineers do.

3.5 Technology in schools

How does this then relate to school technology?

Williams claims that "Beliefs about technology will determine the content of subjects called technology, and will also determine how they are to be taught." (Williams, 1996, p. 31) He therefore suggests that philosophy can be used as an instrument to design curricula, and used by the individual teacher who plans and teaches technology: "A clearly articulated philosophy is one way toward a heightened sensitivity to the challenges of professional responsibility" (Williams, 1996, p. 27).

In her thesis, Inga-Britt Skogh (2001) describes how girls who have had technology and design, enjoy it as an activity, and also that they have accomplished something, but, that many of them do not recognize school technology as "real technology" (Skogh, 2001, p. 131). She continues: "few girls associate the term technology to industry and environment or to traditional home-technology, such as washing clothes, sew, cook" (Skogh, 2001, p. 137) One mother comments: "Going from appreciation [of technology] she now just thinks of it as repetition, the same all over again." (Skogh, 2001, p. 168)[17] Although the thesis shows that girls have achieved self-confidence in technics, and in a nice way describes the happiness the children show when they succeed, it also shows that something is missing. This "something" is according to Williams possible to find through a philosophical inquiry. The questions that Skogh herself asks are:

- How can we strengthen the girls' self-confidence in technology?
- How does the technology and design course influence the girls' attitudes towards technology as a subject, and as a profession?
- What experience of technology do girls have from home, school and other places?

---

[17] ibid. ”Från att dottern tyckte det var roligt [med teknik] tycker hon nu bara att det är repetition, samma sak om igen” my translation

The questions that also ought to be posed may be:

- What is technology?
- What implications do children's and teachers' attitudes to technology impose on the teaching?
- How can history of technology help the children to take interest in technology and technology as knowledge?

What is technology?

If one does not ask the question "What is technology?" it is very likely that one or more of the analytical categories that Mitcham suggests gets omitted. Even if I in my categorization would like to consider technology as being a process, in the way Hickman describes Dewey's philosophy of technology, and consider the skills and procedures a sub-category of technology as knowledge, it is important to consider all the four aspects: Technology as object, Technology as activity, Technology as knowledge and Technology as volition. Technology as object and activity are the most obvious aspects, and they have been considered in all curricula that deal with technology. Often in the Swedish curriculum it has been placed together with craft (Swedish: slöjd). But just to make things, is not enough. If it becomes only activity it gets dull, as the mother says in the citation from Skogh above, which resonates with Heidegger (1954/2003, p. 255) who claims that a necessary view of technology is a creative, aesthetic, *poiésis*, in order to make technology something that opens up new views, something that does not only repeat itself, something that is too ordered. If technology education would search for this opening-up, revealing, then technology would become more than technics, and the subject become more interesting.

If we turn back to the foot-pedal trash bin, this would imply that we not only build the bin, but also talk about the levers, and how these are linked to each other, how the forces applied onto one of them is distributed to the others, so as to lift the lid, but also allow time for a discussion about what more this mechanism can be used for, i.e. let the students use their imagination, challenge their thoughts, as Dewey (1916, p. 179) puts it, or when the students build their electric circuit, not only discuss whether the bulbs in series or the bulbs in parallel give the brightest light, but also in what applications it would be better to use parallel or series circuits. The electric circuit is probably more difficult for as well children as teachers to find more applications to, than the mechanical idea with the levers, and thus the electric circuits become more boring than the foot pedal bin (Skogh, 2001, p. 144)[18].

The aspect which is often left out is "technology as knowledge", although knowledge is the primary aim of schools. There are several reasons for that. One reason is to view technical knowledge as only skill, or possibly tacit. Traditionally the school subject technology has been considered a non-academic subject, and in Sweden it was not mandatory, but a subject

---

[18] Skogh describes which experiments the girls found exiting or boring in her study. Most fun were, "the room" (rummet) the technical museum (tekniska museet), balloon cars, bridges, soldering, and building with peas. The boring were the DC-motor, the lever, the electric switch, measurement instruments and transmissions

chosen by students who were not so interested in schooling (Eggelston, 1994, p. 25). One problem is also that even though “technology as knowledge” consists of both theoretical and practical knowledge, the academia has considered the theoretical knowledge finest, thus a conflict is embedded in the school-subject technology as well discussed by Eggelston (1994, pp. 24-25) as Williams (1996, p. 38). The discussions on which is “the finest” still implies prejudice thoughts about who is the more clever, the bicolour who invents things or the engineer who constructs at his table, a conflict still affecting mechanical industry today.[19] Williams establishes: “A balance must be maintained between theory and practices, and between method and product.” (Williams, 1996, p. 38)

Let’s use the foot-pedal bin again: To make a foot-pedal bin is of course fun, since it is a product the child is familiar with, and can make work, and can understand. As well the theoretical as the practical are necessary in order to make technology fun.

How can history of technology help the children to take interest in technology and technology as knowledge?

That the visit to the Technical museum was one of the more interesting activities in Skogh’s course may be attributed to the possibility to learn not only about things, but also about how the things are made. One of the examples of exhibitions at the museum is Christoffer Polhem’s mechanical alphabet which is a set of mechanical mechanisms, e.g. different transmissions, levers, etc. that Polhem designed and craftsmen built for his Laboratorium Mechanicum in 1697, a school for learning mechanical design. The alphabet is not only something you just look at but rather experiment with. For some children these experiments may only become a fascination snap shot, but for others these may through further discussion with an adult lead to a permanent interest. Many engineers in my circle of acquaintances would mention these types of experiences as their motivation for the choice of profession.

One advantage with the historical perspective is also that the early technology usually is more comprehendible than modern technological objects, like cell-phones. Even technological objects that where possible to understand some years ago, e.g. cars, motorbikes, sewing-machines are today so complicates, that even people with technical education do not understand how they work. By looking at history we can also see that the technical development has been driven by a will to change the world for the better, although there are many examples of technology affecting the environment negatively and also exploitation of people. To discuss what future we would like to have, to take care of the environment and each other are common aims for the school, and to integrate these aims in the technology education becomes natural in the historical perspective of technology. History also challenges us regarding knowledge itself: How could they invent all these ingenious technologies that we take for granted today? Through history we can integrate all the philosophical aspects of technology, mediate fascination, but also give the children the opportunity to discover and invent. History of technology shows that it is possible to work with technology also outside of the school, and that technology can be fun also in real life, outside of the classroom. It shows

---

[19] cf. the discussion about “What is an engineer” above.

that there are risks with technology, but that it is important to make technology a responsible enterprise, as Hickman calls Dewey's philosophy of technology (Hickman, 1990, p. 196 ff.).

3.6 Towards a philosophy of Technology

Both phenomenology and pragmatism are philosophies very well suited for inquiry into technology: phenomenology because it speaks of opening up and pragmatism for its noting of the actional, dynamic aspect of technology. As well Heidegger as Dewey use ongoing presens or nouns built from verbs to make readers notice the temporal dimension of technology, i.e. both of them define technology as action, not action as one aspect of technology. When Mitcham (1994) discusses technology as action, as one category of technology, he describes engineering design, but concludes that when different authors define what engineering design is, they use terms usually used to define what engineers do in general. However, this does not lead to a change in his view of technology as action as the definition of technology, rather than one category of what technology is.

That he considers technology to be action is what makes Dewey use technology as a metaphor for knowledge. He wants to establish the dynamic dimension of knowledge, that knowledge only exists while it is used as a tool, and then he compares it to technology, where he describes technological tools as tools only while used in action. Hickman (1990) makes Dewey's technology of philosophy by collecting the occasions where Dewey uses technology as his metaphor, and for example compares technology to knowledge.

This dynamic view is very useful in the analysis of technology, since technology has the main aim to produce something, the knowledge of technology is aiming at producing, which Heidegger calls "bringing-forth" or "*poiesis*". But the dynamic view is also one that is problematic in inquiry, since our language is so focused on the "what-question", for instance the question raised in the title of this chapter: What is technology? Answering a what-question directs our thoughts towards answers that are static since the answers become nouns, whereas technological knowledge is dynamic, and thus makes the what-question inadequate.

Another pit-fall is to only ask: What does technological knowledge accomplish? What are the effects of technology as knowledge? Although these are interesting questions in relation to technology as volition and sometimes necessary when investigating tacit knowledge and skills, they have hitherto made many philosophers end their inquiry, when the results of technological activity have been examined. Tacit knowledge is by definition non-verbalizable knowledge, and may only be investigated by the results it renders. Sometimes the only observable is the language used, the artefact designed or the practice itself. This renders a dilemma: Should research stay close to the observables, and only describe those, or should research try to interpret the observables into other categories, e.g. what knowledge is taken-for-granted in this practice. The risk by interpreting is to neglect tacit knowledge, but the risk when staying close to the observables is to neglect the knowledge taken-for-granted in a discipline, knowledge that can be opened up by interpretative research.

Engineering is full of knowledge which once learned is not noticed by the engineer. This is also noted by philosophers of technology, e.g. Ihde (1991) describes how a person who learns to use an axe for chopping wood has to think about as well the axe as how he is using it, but when he already knows how to use it he does not think of it anymore, but can even allow himself to think about other things[20]. If knowledge is dynamic, the analysis of knowledge has to be carried out while the activity is still going on. Dewey talks of tools as having meaning only when in active use and knowledge as being knowledge only when in use (Hickman, 1990, p. 16). Knowledge can thus only be investigated while it is in use. But this is not the same as to say that there is no other knowledge than the action itself, which is a possible pitfall. Whether tacit or explicit, knowledge is what is taken-as-given. Thus to open up for the taken-as-given is to investigate knowledge. New ways to see makes it possible to value what is seen, and thus, to open up for professional knowledge, whether tacit or academic, is to value the work done by professionals.

But, as in all inquiry, at least in a phenomenological tradition, it is the untiring task to keep moving towards new horizons, opening up new views, and not as in science try to find a "*final solution*" or "*close the case*". We have already discussed the attraction of the question about the relations between science and technology. That question seems always to end by the "*conclusions*": science is not the same as technology, technology preceded science historically and technology is not applied science. But these are "conclusions" instead of starting-points for new viewpoints. Technology is different from science also in this respect: Technology opens-up for new possibilities, new products, new solutions to problems; Science closes the case, tries to find a conclusion, one answer to the problems, etc. Even the vocabulary used in the two disciplines is different, e.g. conclusion – closing in science, compared to solutions – (etymology loosen up) opening-up in technology.

Some openings for a philosophy of technology – especially technology as knowledge

Phenomenology and Pragmatism

Phenomenology and pragmatism began both, in a broad sense, as radical philosophies of experience and were historically born at the same time, although on different sides of the Atlantic Ocean. In 1993 Ihde introduced the term Post-phenomenology to denote a "nonfoundational and nontranscentdal phenomenology" (Ihde, 1993, p. 7) Phenomenology contributes with a "rigourous style of analysis [and a] deeper phenomenological understanding of embodiment and human active bodily perception, and a dynamic understanding of a lifeworld as a fruitful enrichment of pragmatism" (Ihde, 2009, p. 23) and he "sees in classical pragmatism a way to avoid the problems and misunderstanding of phenomenology as a subjectivist philosophy … locked into idealism or solipsism" (Ihde, 2009, p. 23). Ihde's postphenomenology extends beyond classical pragmatism as well as classical phenomenology in its interest in philosophy of technology by concrete empirical

---

[20] He also gives the example of the blind man's cane, which is no longer an object by which the blind man can see, but his very eyes; the blind man says: "I see …" (p. 30, taken from Merlau-Ponty), the hammer which the carpenter does not think of when it works, but only when it breaks (p. 52 from Heidegger)

studies of the role of technologies in the life-world of humans. “Technologies and humans constitute themselves in interactively” (Ihde, 2006, p. 272), i.e. technologies are not neutral and technologies as well as humans are changed in the process. Ihde is, in his analysis, interested in what is opened up by technology and humans in this process.

To open up and to see technology as dynamic movement towards new ideas, theories, processes and products, and not as given static best theories, procedures and things, is to combine phenomenology and pragmatism. The revealing that Heidegger talks about has this dynamic dimension, although action may be easier to see when looking with pragmatist eyes. Heidegger warns us to make the ordering our main task, since it makes us stop at the enframing, i.e. to see and admire the scaffolding instead of the building that is being built (cf. chapter 3.3). Thus phenomenology helps us keep on opening up.

Knowledge in action

The knowledge that engineers make use of has been a question for some philosophers, usually coming from engineering. Mitcham uses the categories:

- Sensorimotor skills or technemes
- Technical maxims, rules of thumb or recipes
- Descriptive laws or technological rules
- Technological theories, divided into substantive and operative

(Mitcham, 1994, p. 193)

There are other suggestions. Vincenti (1990, p. 208) suggests: fundamental design concepts, criteria and specifications, theoretical tools, quantitative data, practical considerations, and design instrumentalities and Ropohl (1997): technical know-how, functional rules, structural rules, technological laws and socio-technological understanding. Whether these categories are the most appropriate for philosophy of technology and maybe also for engineering, would be a very interesting research question. de Vries (2005) takes on this task by studying a completely different area of engineering, by studying the development of materials for integrated circuit design. More work is still to be done.

Knowledge for action

When Mitcham describes technology as activity he discusses crafting, inventing, designing, manufacturing, working, operating and maintaining (Mitcham, 1994, p. 210). He also describes what engineering action may consist in, invention, design, production, testing, management and sales, and presents this graphically (Mitcham, 1994, p. 216). In many engineering disciplines today there is research going on that tries to identify the necessary steps in engineering processes. For example in systems development (information technology) a lifecycle for a system consists of problem/opportunities identification, analysis, design, development, implementation, maintenance, evaluation. There are tools to use as well in the identification process, (i.e. use cases (Apelkrans & Åbom, 2001)) as in the analysis (requirements engineering[21]). A recent text-book on computer technology has even got the title: “Technology in action” (Evans, Martin, & Poatsy, 2006), because the authors want to mark that they have focused on what can be done, and learned through the use of computers, instead of the more traditional focus on hardware. To make a thorough investigation of these procedures of engineering is beyond the scope of this chapter, but illustrates an area where philosophical inquiry has still much to do. To compare different disciplines’ approaches would probably be beneficial as well for the engineering enterprise as for the philosophy of engineering.

Action for knowledge

To learn from engineering activity, is a common aim with lab-work. But to study what is going on during lab-work makes it possible to analyze what is necessary to know in order to carry out a certain action. Some of the knowledge in a lab is procedural, and some is conceptual. Although these two often are used as descriptive categories, in the analysis of knowledge the divide is rather between the object/event-world and the theory/model-world. To study lab-work is to study action that is giving knowledge, i.e. to study action for knowledge.

Action in knowledge

In Dewey’s comparisons between technology and knowledge the main remark is that knowledge is in action, as well as technology is in action. Both are action, both are dynamic. To study technology, knowledge and learning is to study action. One action which is possible when knowing is to talk about what one is doing. Thus one way to study knowledge is to study action. One way to study action is to study language, another to study the action itself. In education it may be to study both for instance during lab-work. To study language is to stay close to the observables, but to study what other actions come from a sequence of talk can give even more. When analyzing the students’ talk while learning technology one can also interpret what kind of knowledge there is to learn, what is possible to learn from the situation, what is not possible to learn, what is taken as given in lab-instructions as well as what is taken as given initially and thus not noticed by the students.

Revealing – to open up for

Knowledge in a discipline is that which is taken-for-granted by those who work in the discipline. To teach is thus to open up for that which is taken-for-granted. To carry out research in education must thus be to *open up for the opening up of the taken-for-granted*. That is the itinerary that I will take on as my next journey, and the following chapters of my thesis.

---

[21] Ongoing research at the School of engineering, Jönköping, Department of Information Technology

4 Theoretical frameworks

The aim of the thesis is to

- develop a model: The learning of a complex concept
- show how this model can be used as well for analysis of the intended object of learning as students activities during lab-work, and thus the lived object of learning
- use the model in analysis of what changes in instruction that are critical for student learning.

The choice of research question, data collection methods and theoretical frameworks all have impact on what is possible to investigate. When the research question includes the learning process, as is the case when studying how students link different kinds of knowledge, the most apparent method would be to study the authentic setting, i.e. to study the lab-situation directly. On the other hand, to study the lab-work by means of video-recordings, makes it impossible to work with large populations. In my work I have found it fruitful to use different frameworks since these highlight different aspects of my questions.

I will start this chapter with a presentation of the three theoretical frameworks that I have been working with, present my own contribution to theory, and finally discuss how these contribute to the ways of seeing and changing the ways students work with labs.

All three theories are "starting from the purpose of this [the particular teaching/learning sequence] practice as formulated by the teacher" (Wickman, 2004, p. 342), "the intended object of learning" (Marton, Runesson, & Tsui, 2004, p. 4), and are thus "opening up a new and previously inaccessible way of thinking about something" (Land, Cousin, Meyer, & Davies, 2005, p. 53), in other words, all three start from learning of something specific, try to find a way to see how students learn, to make learning possible, and to analyze how this learning is made possible.

4.1 Variation Theory

Variation theory takes its point of departure in phenomenology. Learning is described as a change in the way of seeing: from being aware of a few scattered aspects, to a more holistic view of the phenomenon. Learning is seen as a "change in awareness of the whole area and its constituents and the relation between them" (Booth, 1992, p. 7). Variation theory focuses the relation between the learner and what is learned, in phenomenology called the *intentionality*: "every experience has its reference or direction towards what is experienced, and contrarily, every experienced phenomenon refers to or reflects a mode of experience to which it is present." (Ihde, 1986, pp. 42-43) In relation to learning *intentionality* can be expressed as: "Learning is seen as a qualitative change in the relation between the learner and that which is learned, which can be expressed as a move from one way of seeing the phenomenon to another or, equivalently, as the phenomenon appearing to the learner in a qualitatively new way compared with earlier appearances. The relation is bipolar – the learner sees the phenomenon in a particular way and the phenomenon appears in a particular way to the learner." (Booth, 2004, p. 11)

Variation Theory discusses the relation between *the intended object of learning, the enacted object of learning* and *the lived object of learning*, and states that no learning is possible unless there is variation, variation of that which is to be focused upon in the learning situation.(Marton & Tsui, 2004) The *intended object of learning* is what the teacher had intended for the students to learn. Often this is something teachers would have as a common aim, e.g. to learn time, by learning the clock (Holmqvist et al., 2007), or to learn to handle fractions (Runesson & Marton, 2002). The *enacted object of learning* is what is made possible to learn. What is made possible to learn, are such aspects that the teacher focuses on through the variation that is opened up, e.g. the time hand's position when learning time, or varying part/whole and division/quotient aspects instead of the numbers used or solving strategies when learning about fractions. The *lived object of learning* is what the student actually becomes aware of, and thus changes his ways of seeing.

Variation is necessary in order to learn something, and interestingly it is what is to be focused that needs to be varied. If we want to learn the colour "blue" it is not adequate to vary shapes and objects that are of the same blue colour, but we need to vary the shades of blue, and even contrast it to what is not blue. If we vary both shapes and colour at the same time, it will be more difficult to learn what is blue. So what to keep invariant is as important as what to vary. If we want to learn relationships it is necessary to vary those in specific ways, e.g. part/whole relationships, when learning fractions, and vary them simultaneously. This simultaneity may be diachronous or synchronous, which means that we need not talk about both aspects of the relation exactly at the same time, but need to make both aspects be in the learner's awareness simultaneously.

To see something in a new way requires that the learner discerns new aspects of the phenomenon to be learned. It is thus also important that the students learn that learning is to discern, i.e. "develop capabilities for seeing or experiencing situations or phenomena in certain ways." (Bowden & Marton, 1998, p. 24)

What to vary, and how this variation is to be carried out in the classroom, are often subtle details, only possible to notice for a person with deep understanding as well of the subject matter to be taught, as of what is critical to notice, to be aware of, in order to develop deep understanding. What to vary could be called *critical aspects*, and in what ways these can be varied could be called *critical dimensions*.

The Theory of Variation offers as well a method to analyse teaching sequences, as a method to analyse learning. According to Runesson and Marton, learning amounts to "discerning critical features (or aspects) of objects and situations and focusing on them simultaneously" (Runesson & Marton, 2002, p. 35). When analysing what is varying and what is kept invariant in different teaching sequences it is not only possible to discern what is made possible to learn, but also what is taken for granted by the teachers, and thus not made explicit. To develop teaching sequences is thus to discern critical features, that available teaching sequences offer or take for granted, and by focusing upon those features which give the closest relationship between the intended and enacted objects of learning, development of teaching sequences will be improved.

4.2 Practical Epistemologies

A recent theory specifically aimed at studying learning through practical work is “practical epistemologies” (Wickman, 2004). It focuses the process of learning during laboratory work, and takes its departure from pragmatism, where knowledge is action as well as in action. Talk is also seen as action, thus to study what is said, is to study the learning process. “Practical epistemologies are descriptions of people’s ways of making meaning in action.”(Wickman, 2004, p. 327). “These [The students’] actions represent their practical epistemologies, i.e. what *they* count as knowledge and how *they* get knowledge *as acting participants* in the laboratory practice.” (ibid., italics in original) Practical epistemologies concerns learning approaches, students’ courses of action, and meaning-making.

Four labels are used in the analysis of students’ talk during labs: *stand-fast, encounter, gap* and *relation*.

“What stands fast in a certain practice is used as points of departure in encounters with the world in speech and in action.” (Wickman, 2004, p. 328) In order to be able to communicate there has to be words and actions that stand fast, words and actions that do not need to be negotiated, in the particular situation, e.g. when someone asks “reach me the towel”, there is normally no need to discuss what a towel is. The meaning of the word “towel” thus *stands fast*.

When a person interacts with something in a situation, this is called an *encounter*. This “something” can be what is said or done, or can be physical objects. Typically in education an encounter is when a student notices something that is new to him, or that appears in a new way or in a new situation. Encounters can involve as well direct as recalled experiences.

When people encounter something, a *gap* between what stands fast and the encounter occurs. If the gap is *noticed*, they try to establish *relations* between what stands fast and the encounters, they try to *fill the gap*. “If the gap is not filled eventually, the current activity or theme of discourse stops, and a gap will linger.” (ibid., p. 329) In a teaching/learning situation it is thus as important that students notice the gaps as it is that they fill them.

For pragmatists, to study learning is to study change in actions and speech. Thus to study which gaps occur, how students notice gaps, and how students try to fill gaps are important entities of analysis. To enhance learning is in this philosophical context rather to make it possible to notice the intended gaps, sequence the encounters, and lead the students towards ways of speaking and acting approaching the scientists’ use of language. Especially to look for *lingering gaps*, i.e. when the activity cannot go on is in this study shown to be a fruitful way to find what in the educational setting needs to be changed.

When looking at students' practical epistemologies it is possible to see how they learn, e.g. the "complexity and situativity of their habits" (ibid. p.339), and how they sometimes do not act in intended ways, e.g. the "incoherent ways in which students treated the relations" (ibid. p. 339). It is also possible to see how the teacher helps the students to decide on what counts as relevant knowledge, something that has been shown by other studies as well (e.g. Barnes, 1976; Bowden & Marton, 1998; Malmberg, 2007). Actions taken, actions not taken, the order students notice and fill gaps, or do not, can be used to learn more about how the teachers' interventions help – or do not help – students in their process of meaning-making. We can observe "how a practical epistemology … can be used to understand the course students' learning takes in interaction with events that the teacher can change and influence in school work." (Wickman, 2004, p. 340)

4.3 Threshold Concepts

In many fields of higher education it is possible to recognize 'threshold concepts' (Land, Meyer, & Smith, 2008; Jan H. F. Meyer & Land, 2003; Jan H. F. Meyer & Land, 2006), concepts that are *transformative, irreversible, integrative* and *troublesome*. These concepts are of special importance, since a deep understanding of them is necessary for learning other concepts. Examples investigated are e.g. recursive functions in computer engineering (Booth, 2004), confidence interval in statistics (Cope & Byrne, 2006) and opportunity cost in economics (Davies & Mangan, 2008). All of these are difficult to learn, and if not learned in a deep way, they hinder the students from learning following topics. They are *transformative* since they change the ways students go about learning other things, they see things in new ways which opens up for new ways to learn. They are *irreversible*, since once learned these concepts cannot be viewed in the old uninformed way, the old way of seeing seems forgotten, while the new way to see cannot easily be forgotten. Threshold concepts are also *integrative*, "exposing the previously hidden interrelatedness of something (Jan H. F. Meyer, Land, & Davies, 2008, p. 67)." Typically this interrelatedness belongs to the intended object of learning, but is not explicitly enacted, as I will come back to in my results. Buildning on Perkins (2006) threshold concepts are *troublesome* to learn. Many students hesitate to engage in the activities meant to help them learn, often because they do not see where the activity is going to take them, 'the portal is still blurred'.

4.4 Key concepts – my contribution to theory

In a pilot study I introduced, what I called, *key concepts*, concepts that facilitate learning of also other concepts than the one introduced (Carstensen & Bernhard, 2002). In the pilot study it was shown that by learning the Bode Plot in a particular way, students also learned other parts of a course in control engineering, parts not explicitly taught but required in the exam. "We use the term as a more precise metaphor to mean that the concept in question acts like a key to *unlock* the 'portal' of understanding, the 'portal' which opens up for learning of other concepts" (Carstensen & Bernhard, 2008, p. 143), and "not in the sense that the term is often used in some educational contexts, as interchangeable with ‘core’ concepts, and meaning simply that the concepts are an important part of the prescribed syllabus.” (ibid.)

To introduce *key concepts* is a way to distinguish between concepts that are troublesome, and concepts that makes it possible to learn, i.e. between the problem and possible ways to solve the problem, in old terms: misconceptions and how to teach them. To introduce key concepts is to open up for learning and not just stop where the problems are recognized, as many texts on educational research do. In the case of Bode plots (from the pilot study), the threshold concept would be frequency response, and the key concept would be to teach Bode Plots according to variation theory, and in the study presented here, the threshold concept would be transient response, and the key is found to be systematic variation of transfer functions, as well mathematically as in simulations and measurements. In both cases the key opens up for making links between concepts to make the learning a learning of a complex concept, and not just single concepts of knowledge.

4.5 Why different approaches? – How do they meet?

Do we need all these theories, and are they commensurable?

The first thing to explore in order to acquire indications on whether theories are commensurable is to examine the language used and possible to use. Obviously it is possible to view phenomenology and pragmatism as philosophies that define knowledge, especially technological knowledge in action. Both speak of learning for action as well as action for learning. Pragmatism studies learning while learning is going on, through studies of what is said or done. Phenomenology studies what is opened up for learning, the enacted object of learning and what is experienced as ‘the lived object of learning’.

The next thing to discuss is what aspects different methodologies can open up. The tradition behind variation theory is to use semi-structured interviews where students are asked about their conceptions of a concept. This leads to a categorisation of qualitatively different ways to experience the phenomenon, “different ways of being aware of the nature of” the phenomenon (Booth, 2004, p. 13). These categories span from learning of simple facts through recognizing some related facts to a more expert-like view. Thus the categories are inclusive. When the research question deals with learning through lab-work, it seems relevant to study what students do instead of what they recall afterwards, but the data from video recordings of classroom-sessions is very rich, (a great deal of data to analyse, as well as long sequences where ‘nothing’ happens) and thus it is difficult to discern phenomenographic categories (Marton & Säljö, 2005). There is also a risk that things taken for granted are not reflected through the interviews, or that ‘well-known’ facts, pre-established categories are reflected instead of actual.

Another problem with interviews is that it can be rather difficult to ask the right questions. It is important not to direct the answers towards expected answers, but also to be open for unexpected answers, which urge for follow-up-questions. When interviewing students, there are problems associated with asking the students directly what they consider ‘troublesome’.

Several reports show that the students' own descriptions of what is difficult do not always agree with those provided by an expert (Harlow, Scott, Peter, & Cowie, 2011). This is especially so when interviews are conducted with students who are still novices: it has been shown that students may not consider something they have yet to understand as being difficult. One example is that mathematics is considered difficult, and in an interview this is the answer you get (Entwistle, Nisbet, & Bromage, 2005) although we show, that it is not the mathematics itself, but knowing when to apply what, i.e. to link mathematics and mathematical results to measured data and theoretical knowledge, that is difficult.

By using 'practical epistemologies' it is possible to analyse the lab-work directly. This method lends itself to view what is actually going on in a learning situation - what questions are raised, what courses of actions do students take, what relations do the students deal with, what relations do they not notice, etc. It is also possible to study what relations the teachers open up for, what encounters teachers help students notice. "There are numerous relations that often are taken for granted by people that already master a specific practice. As these relations often reveal themselves only as part of an activity, the novice needs to learn them in encounters in a practice with an authority (cf. Wittgenstein, 1968). The teacher in turn needs encounters with the learners to notice that such gaps must be filled." (Wickman, 2004, p. 342) Also Davies and Mangan discuss how the relations that are taken as given can be revealed through investigation of practical exercises: "the dimensions become visible through the use of the procedures" (Davies & Mangan, 2008).

Learning Studies is another method to study learning while it is going on, and has been developed as a method in Variation Theory research. Teachers and Researchers jointly develop lesson plans, video record instances of the teaching, analyse these recordings in order to find critical aspects for learning, and refine the plans in an iterative process. Our study has many similarities with a learning study, especially the search for critical aspects in as well intended as lived objects of learning, However, since we are studying what students do and say, we found practical epistemologies to facilitate the search for critical aspects in the enacted object of learning. Especially what the students do not do is of great importance and is highlighted by the practical epistemologies, since what they do not do or notice renders lingering gaps, that are caught by this method. Another problem that we encounter is that the course we are studying is a course only given once a year, and yet the curriculum is often changed between years, making it difficult to make iterative refinements.

To open up for learning is to open up for that which is taken for granted, and to learn about what is taken for granted is to do research on what is taken for granted, i.e. to open up for the opening up of that which is taken for granted (cf. chapter 3.6)

5 Review of relevant previous research in electrical engineering education

There is still very little research in engineering education, and especially electrical engineering education. Also journals that are specifically aimed at engineering education, still have more of "try this fancy lab – it is fun and students learn a lot from it" than research. In recent years the interest in engineering education research has emerged, but still very little is written in electrical or control engineering education research. There are some exceptions, that will be described below, the ETL-project (Entwistle, Nisbet, et al., 2005), electric circuit understanding (de Oliveira & de Oliveira, 2010; González Sampayo, 2006; Harlow et al., 2011; Kautz, 2008, 2011a, 2011b; Ryegård, 2004) control engineering (Fraser & Linder, 2009; and Lamont et al., 2010), and modelling in analogue circuit design (Malmberg, 2007). Interestingly the choice of topics are rather similar, dealing with mathematics laden courses, and how to become a skilled expert. Some examples also of the more common kind ("tips and tricks"), although not research in engineering education research will be mentioned, and argued interesting choice of research topic, but not yet ripe enough to count as research in this field.

Entwistle (2005, p. 1) stated "There has been a substantial amount of research carried out into how teaching affects learning in higher education but there has not been a ready take-up of the ideas in university departments. Part of the reason is that the research is generally reported in education journals and in social science jargon, and part is the realisation that the findings cannot be applied equally well to the wide variety of disciplines and professional areas." In the final report of the ETL-project (Entwistle, Nisbet, et al., 2005) the authors also describe that "there were *ways of thinking and practising* (WTP) in each subject area", which may make it difficult to implement research results into the education, unless the research results come from the specific area of education. In other words, it is important that research in engineering education is carried out in each area of engineering. It may also be problematic to inform engineering education by research due to the perceived difference between educational research and engineering research:

> "One of the problems in introducing educational research findings to colleagues in other disciplines is that the nature of the data collected, the analyses carried out, and the ways in which conclusions are reached, can be very different to those adopted in other research areas. The contrast with the types of research carried out in engineering is particularly marked, leading to the following comment from engineers in the USA about attempts to encourage staff to use concepts and research findings from educational research to develop a *scholarship of teaching* within the subject.
>
> > *It is almost impossible to conduct an educational research study in which potentially confounding factors can be clearly identified and their influence eliminated… [Educational research does not use] the kind of reasoning engineering professors are accustomed to employing in their research... and most of them are skeptical of it. A large part of the challenge of legitimizing the*

> *scholarship of teaching in engineering education involves overcoming this skepticism. (Wankat et al., 2002, pp. 227-8)*
>
> The evidence collected in any educational research study can never be as precise as that engineers are used to, rather different kinds of evidence are used to lead towards sustainable conclusions. In spite of some understandable wariness about the nature of the research process, we generally had a great deal of help and support from both staff and students that allowed the study to progress in the ways intended." (Entwistle, Nisbet, et al., 2005, p. 5)

The two most challenging results in the report are that:

> "The specifics of analogue electronics engineering that were highlighted through the ETL-project were that students "are faced with contrasting representations or models of a circuit - the actual circuit, the circuit diagram, simplifying transforms of it, algebraic solutions, and computer simulations. Students have to move between these different representations in solving problems or designing circuits and they also need to understand the function of a circuit in both practical and theoretical ways – the engineering applications and the physics of how it behaves." (Entwistle, Hamilton, et al., 2005, p. 9)

And

> "In analogue electronics, an additional difficulty seems to be that understanding involves both analytic skills and an 'intuitive' grasp of circuit characteristics - intuitive in the sense that the characteristics of analogue circuits are less transparent and predictable than digital ones. Students thus have to build up substantial experience of the properties of many different kinds of circuit before they can 'see' what lies behind any new circuit diagram they meet or can decide what type of circuit will be required in a design problem." (Entwistle, Hamilton, et al., 2005, p. 9)

Both of these resonate with this research work; the first one we try to meet by modelling the representations, and the second by modelling the activities that are necessary for learning. The representations are seen as contrasting in the statement above, and our model is an attempt to make them not contrasting but instead complementary and connected, we make an attempt to make a whole of the parts that are constituted by the different representations.

An almost simultaneous work was carried out by González Sampayo (2006). She discusses what it means to become an engineer in terms of the *techné-pyramid* (Figure 9), where the bottom is to learn basic concepts, the following level courses that include analysis of more complex concepts and on the top-level the knowledge is used for design purposes.

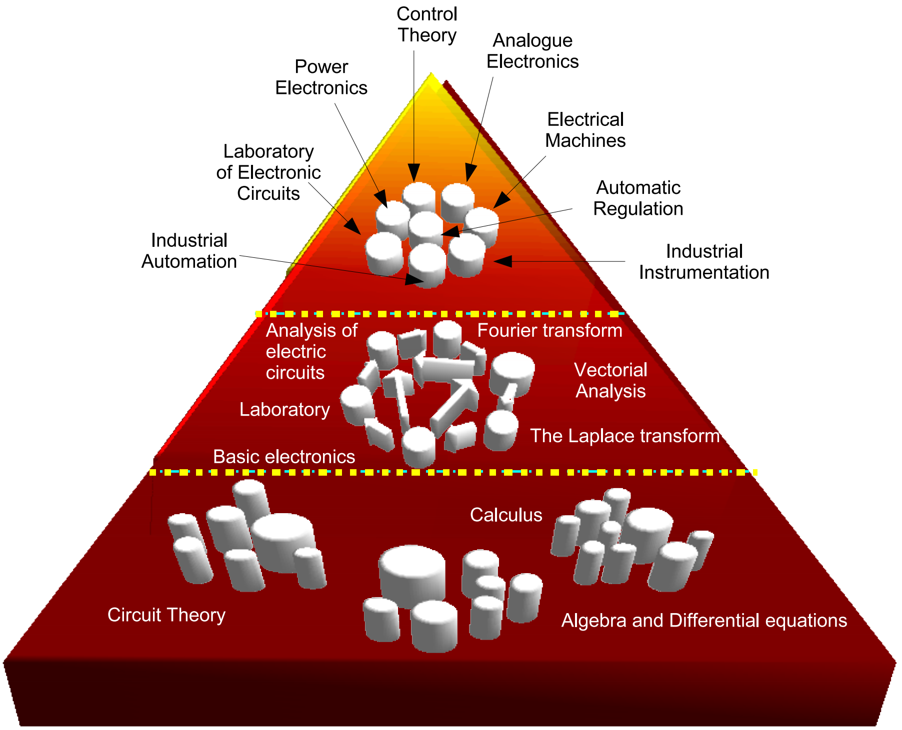


Figure 9: The Techné-pyramid showing how circuit theory appears in several courses throughout electrical engineering curriculum and at different levels: basic level, analysis level and the design level (González Sampayo, 2006, p. 139)

Here the important issue is that skills and conceptual knowledge cannot be separated, but indeed need to be merged into a holistic knowledge. She shows that when some of the basic concepts are not learned it is not possible to appreciate knowledge at the next level and that if the necessary mathematics is not applied in an appropriate way, e.g. using the Laplace transform for problem solving of transient response in control engineering, students may not reach the design-level.

These ideas resonate with the ideas of Malmberg (2007) who claims that if the design process is not clearly advocated at university, the electronics engineering students will when they start working in the industry, “have to relinquish the theory knowledge from their university studies, since the students are not equipped with the knowledge how to use those theories in practice.“ (Malmberg, 2007, p. 82) He describes a structured process for analogue circuit design, where calculations of the kind learned at university can be efficiently used together with measurement data presented in data sheets, simulations or own measurements, to build and make use of experience. His categorization of knowledge builds on Aristoteles, thus *episteme, techné* and *phronesis* are exemplified in terms of the subject specific knowledge that belongs to each category. He makes a model “the expectation method” (Malmberg, 2007,

p. 106) which may be used to gain and make use of experience, in which phronesis related to both *episteme* and *techné* are developed and used to more efficiently design new circuits.

Both of these bodies of research try to analyse what it takes to become a design engineer, which to Mitcham seems to be a tautology since he concludes his discussion on technology as action by: “The problem is that the standard engineering definitions of designing do little more than rephrase the standard definitions of engineering itself” (Mitcham, 1994, p. 220). This may not be a problem, rather, to explicitly claim that engineering is *to design*, and *to apply theoretical knowledge in practice,* may help to gain explicit knowledge about *phronesis*, often called *tacit knowledge*, especially if this knowledge is modelled to highlight what learning of this *phronesis* may be.

When Entwistle, Hamilton, et al. (2005, p. 9) speak of the specifics of learning electronics as ”analytic skills and an ‘intuitive’ grasp”, this resonates well with Malmberg and Gonzalez. All of them discuss the problematic divide between theory and practice, and their discussion tries to make sense of what engineers commonly talk about as “to apply theory to practice”. (Ryegård, 2004) makes another definition: interactive knowledge, which she illustrates by a figure:

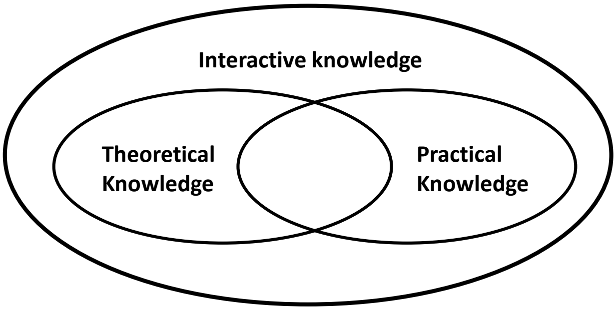


Figure 10: Interactive knowledge (Ryegård, 2004, p. 31)

Ryegård includes practical work into the lectures and shows that when students work with as well theoretical as practical tasks simultaneously they gain more knowledge than when they have traditional lectures and separate labs, which was the case in the control group. The students in the experiment group show considerably more practical knowledge, and make at least as good as the control group on theoretical tests. In the discussion the interactive knowledge is considered not just to be the sum of the theoretical and the practical knowledge but something more; as illustrated in the figure above, the interactive knowledge includes both the theoretical and the practical, but something more is added.

When we choose to work with the model (Tiberghien, 2000) we do it for two reasons: it focuses the links between theoretical and practical knowledge, that are necessary for learning the whole, and it makes the specific content knowledge explicit (in both worlds). One of the most important features of this model is that practical knowledge is not confused with procedural knowledge, which is often the case when practical knowledge is discussed.

Ryegård makes very clear that as well theoretical as practical knowledge make use of procedures, and that skills are necessary both when working with modelling and practical measurements, and thus recognizes this categorization problem.

I will come back to these models in the chapter dealing with modelling of a complex concept in chapter 7.

The learning of basic electrical concepts (current, voltage, impedance) in DC-circuits are dealt with in as well science education as in higher education research, since questions like "Can there be current without voltage?" and "Can there be voltage without current?" and other similar questions cause problems for students as well in schools as at university (e.g. Koponen & Huttunen, 2012; McDermott & Shaffer, 1992; Periago & Bohigas, 2005). Several of these studies show examples of local reasoning (e.g. Cohen, Eylon, & Ganiel, 1983; Duit & von Rhöneck, 1997; McDermott & Shaffer, 1992), where students keep one of the three variables (R, I, V) constant even when all three change. González Sampayo (2006) shows that some of these problems remain after introductory courses university studies, and that this is a problem that is common in several countries. Recently Hussain and her co-workers (Hussain, Latiff, & Yahaya, 2012; Hussain, Salim, Haron, Ali, & Hussain, 2013) have demonstrated that this is also valid among Malaysian electrical engineering students.

Streveler et al. (2006), identify 27 different concepts in electrical engineering as being important and problematic for students. Although all are relevant they are all contained in the more complex concepts that are brought up by engineers doing research in their own field. The concepts that have been highlighted by research in electrical engineering education are basic electrical concepts, frequency response, Thevenin's theorem (also called two terminal equivalents or equivalent circuits), transient response, and analogue circuit analysis (in some of the research papers called dynamic resistance, small-signal analysis, or load lines). Also learning to program is subject to research, although in this study only two examples will be given.

Thevenin's theorem is an example of modelling a circuit, modelling it as only one voltage source and a series resistor, and often students fail to appreciate the model, since they have problems understanding that it is a model. As well Scott (Harlow et al., 2011) as Foley (2012) consider this and small-signal modelling the two most troublesome, and yet most important issues to learn in analogue electronics. They both suggest that these concepts are threshold concepts in electronics engineering. This resonates well with (de Oliveira & de Oliveira, 2010; Kautz, 2009; Ryegård, 2005), who all have posed broader questions to their students and found these two to be the most difficult DC-concepts.

They have developed sets of problems to solve, where students cannot just use standard methods to solve them, but have to link their knowledge from measurements, calculations and theory. Although their settings are different (PBL, tutorials, interactive lectures) these problems made the students not focus on finding "the correct solution", but to analyse the problem, explore possible strategies, and as expressed by (de Oliveira & de Oliveira, 2010), the teacher interventions were seen as "an opportunity to discuss options which the students had already identified".

Transient response and frequency response are also the topics chosen for research in control engineering education. As well Lamont et al. (2010) as Fraser and Linder (2009) discuss the use of the Laplace transform and the difficulties that students have to appreciate the Laplace transform as a means to simplify the calculation of response to stimuli of different kinds, especially when using simulations to solve rather complex problems. Both of these show that variation of few parameters systematically is important. Lamont et al. (2010) design a task were students are asked to work with a second order system described on one of the normalized forms of the transfer function of a second order system:

$$G(s) = \frac{\omega_n}{s^2 + 2\zeta\omega_n + \omega_n{}^2}$$

.

Students are asked to simulate the output when varying one of the variables, while keeping the other constant, and show that students get a deeper understanding of the second order system by doing so. Fraser and Linder also use this form of the equation and suggests to give students systematically varied examples to solve by hand calculations as well as simulations, where only one of the parameters, ζ is varied. In this they criticize us to vary two parameters (both ω and ζ) since by changing only the last parameter (only ω) also ζ is changed – it is even changed in proportion to 1/ω since ωζ is to be constant. They claim that it would have been more appropriate to change only the second parameter since then only ζ would change. This criticism is however due to the choice of the theoretical constructs ω and ζ and these are actually not independent in a real world applications. The choice we make – search the zeros of the characteristic polynomial – is a theoretical construct which is useful not only to second order systems but to any system:

$$G(s) = \frac{B(s)}{A(s)} = \frac{b_m s^m + b_{m-1}s^{m-1} + \cdots + b_1 s + b_0}{a_n s^n + a_{n-1}s^{n-1} + \cdots + a_1 s + a_0} = K\frac{(s+z_1)(s+z_2)\cdots(s+z_m)}{(s+p_1)(s+p_2)\cdots(s+p_n)}$$

$n \geq m$

For the second order system this is:

$$G(s) = \frac{b_2 s^2 + b_1 s + b_0}{a_2 s^2 + a_1 s + a_0}$$

and the solution to the characteristic equation is

$$p = -\frac{a_1}{2} \pm \sqrt{\left(\frac{a_1}{2}\right)^2 - a_0}$$

(if a2=1, which is usually the case). If we compare this to the normalized form, where

$$p = -\zeta\omega_n \pm \omega_n\sqrt{1-\zeta^2}$$

we can see that whether we change only ζ or only ω, we still change more than one parameter in the solution, e.g. the frequency of the damped sine $\omega_n\sqrt{\zeta^2 - 1}$ for ζ > 1. We claim that by introducing ω and ζ we only bring in another theoretical construct to learn, one that is only useful for second order systems, and more confusing to students than useful in control theory.

I can still remember how confusing it was that the frequency of a damped sine was not ω_n and that it was so difficult to calculate, when it actually is the imaginary part of the solution of the characteristic equation $\sqrt{\left(\frac{a_1}{2}\right)^2 - a_0}$ when $a_0 > \left(\frac{a_1}{2}\right)^2$. To me this is the more straight forward way to work with the characteristic equation. To calculate the poles the same way whether real or complex (and not include an ω when there is no frequency-component), also helps students to understand some of the important properties of the concept of poles, e.g. real poles when $\left(\frac{a_1}{2}\right)^2 - a_0 > 0$ and complex conjugated pairs of poles when $\left(\frac{a_1}{2}\right)^2 - a_0 < 0$, which is important e.g. when pole placement is used for feedback control.

Despite this criticism the research by both these research groups show the importance of varying one parameter at a time (even if more than one real time parameter changes). They also show that by making the students work through this variation by themselves, the students may draw conclusions of what they see and thus can use this knowledge in following experiments and further studies, as opposed to what was the case when students were only shown this in a lecture, put in the words of Lamont et al. (2010, p. 103): “If the instructor advises them on how varying ω_n and ζ will affect the performance of the system, it is likely that students will take it as another piece of information to be learnt and not retain the relationship of the systems transfer function and performance.” They also conclude that “Such techniques [interactive learning] enhance not only the student’s understanding (of how changing a variable can affect system output) but also his/her involvement in the learning process” (Lamont et al., 2010, p. 107). Interestingly the phrase “interactive learning” is here used in the same way as in (Ryegård, 2004). Fraser and Linder concludes: “not only should we be using this sort of variation in our teaching, in which one critically important aspect of a situation is varied while all others are kept invariant, but we should also be using this explicitly, as well as varying the approach taken to the problem. This is so that what is educationally important can come into focal awareness for the students, thus increasing the possibility of learning for them.” (Fraser & Linder, 2009, p. 379)

6 The Empirical study

We video-recorded students' actions and communication during labs in an electric circuit course for first year engineering students. The course had in 2002 (called the old course) 13 lab-sessions lasting two hours, except the last two ones which lasted four hours. Each lab was given four times, to up to 16 students each time (cf. Table 3). Two groups were video recorded each time, rendering videorecordings from 8 groups à 2 students in each (The total number of students in the course was 60). The students also had lectures 2 hours/week and classroom-sessions 2 hours/week. The videotapes were preliminary analysed. The questions raised by the students were in focus of the analysis.

Format (2002)	# times	Length (h)	Total # hours	Nominal # students
Lecture	12	2	24	60
Problem-solving	20	2	40	30
Lab	13	2 (for 2 labs: 4h)	30	15
Total # hours for each student			94	

Table 3: The general organisation of the electric circuit theory course in 2002

The preliminary analysis showed that students very seldom used material from classroom-sessions, although the most common aim of lab-work is to connect theory to practice (Tiberghien et al., 2001). Although both students and teachers answer that the purpose of labs is to explain theory, still most students (only one of the groups 2002 is an exception) do not spontaneously bring their notes from lectures and problem-solving sessions into the lab-room. One of the changes suggested was to integrate labs and problem-solving sessions, so that theory and practice would be more explicitly linked.

Thus in the revised course the lab-sessions and the classroom-sessions have been integrated, resulting in 13 weekly four hour *problem-solving labs* (cf. Table 4). Since the material from the first year was 250 hours of videorecordings, the decision was to only videorecord two groups the second year rendering around 80 hours of recordings, in order to make it possible to transcribe the material and make a thorough analysis.

Format (2003)	# times	Length (h)	Total # hours	Nominal # students
Lecture	13	2	26	60
Integrated problem-solving labs	13	4	52	15
Total # hours for each student			78	

Table 4: The general organisation of the electric circuit theory course in 2003

The labs which are the focus of this thesis are among the last ones – Transient Response. In the old course this lab lasted four hours and the classroom-sessions 2x2, i.e. four hours, which in the new course transformed into two four hour integrated *problem-solving lab-sessions*. Thus the same amount of time was appropriated for this part in both courses.

However, the preliminary analysis also showed that it was important to notice that there were only two qualitatively different kinds of curves, i.e. damped sine-wave and an over-critically damped (there is theoretically also a third, the critically damped curve, which will hardly ever occur). Only one group 2002 did this, and that was the group who made calculations while they were still in the lab-room. All other groups needed help in finding out "what formulae" to use, but also ended each measurement by the questions "Is this good enough for the report". Thus to make the students do calculations in order to find out what curves to expect was important. In the new course 2003, this was enforced in two ways; give students systematically varied examples to solve by hand-calculations and to simulate. The focus would be on the qualitatively different curves, and thus to ask students to draw such curves by means of simulations of the graphs directly from the transfer functions used in the calculations.

The design of a model to analyse the students' actions and communication is described in the next section, and the results in chapter 8.

7 Method – Designing a model and use it for analysis – The learning of a complex concept

In order to keep a balance between detail and overview when analyzing video-recordings, it is necessary to find a method that is not too time-consuming, and yet gives relevant results. In an attempt to find such a method we arrived at a model that has appeared to be useful as well in analyzing what the students do during lab-work as analyzing the lab-instructions.

The model was built upon the model introduced by Tiberghien (2000) and co-workers:

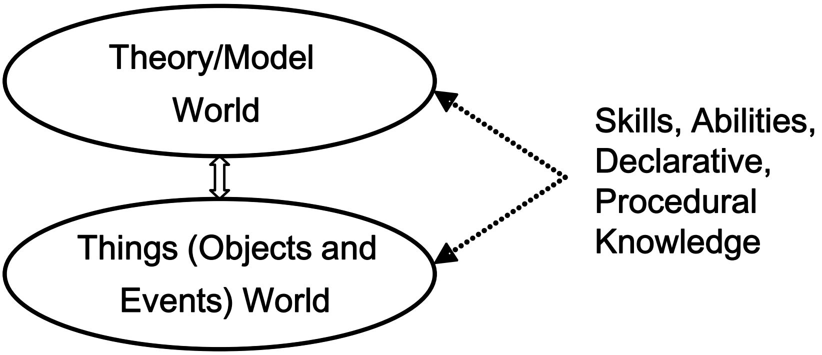


Figure 11: Categorisation of knowledge based on a modelling activity, (Tiberghien, 2000)

The divide is not the traditional between theory and practice, but between the Theory/Model-world and the Object/Event-world. In both worlds there is procedural as well as declarative knowledge, and the relation that students encounter as problematic is the relation between the two worlds, very seldom inside one of the worlds.

This chapter will begin with a short introduction, followed by a discussion of what modelling is about, a discussion on the theory-practice divide and finally the procedure that was used to model the learning of a complex concept.

To learn a complex concept it is necessary to recognize and understand as well the concepts involved as to make the links between those concepts, which in variation-theory is expressed as: “learning is about coming to understand something of importance in a way that is qualitatively more in line with desired goals, and that this is a matter of expanding awareness to embrace greater wholes, more parts within the wholes, and stronger relations between parts – and, in particular, that critical aspects can be brought into focus.“ (Booth, 2004, p. 13) In order to find the critical aspects through modelling the object of learning, the model needs to display as well the parts as the whole.

Starting with the model by Tiberghien and co-workers, we looked at what students were doing in labs, what aspects they were dealing with, and which paths their meaning-making took. We saw that sometimes they were only dealing with one concept at a time, sometimes they were relating different concepts to each other. Drawing a figure from this we achieved our model, which we also could use to analyse what was intended for the students to learn (cf.Figure12)

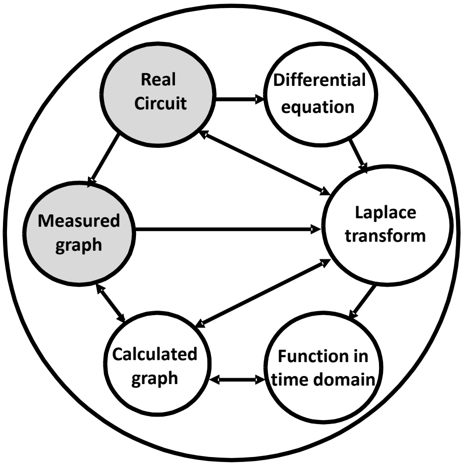


Figure 12: The model of learning a complex concept

In this model *single concepts* are illustrated as nodes or *islands* that may be connected by *links*, represented by *arrows*. The arrows in the figure above show all possible *links to make*, and their directions. The nodes and links 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 thus a *critical aspect*. When a *gap is filled* and the students establish a relation, between two nodes this is re-presented by a *link* (arrow).

7.1 A short detour into the etymology of the word modelling

The word model has its etymological roots in the Latin word *modulus*, the diminutive form of the word *modus* which originates from a standard measure. It was used as a prototype for the measure, and also used to measure. The word model is thus used for making images in both senses, as an ideal to make an image of, e.g. a person who poses for a painter, or acts as a role model, and as the image, the representation of the ideal. Also the word *mold* has the same etymology, which may make it easier to understand why the word is also used for building clay models. The Swedish words that are used to translate the two different models, are *avbild* and *förebild*, where the first is an image from an ideal, and the other an image to use as a prototype. The word "bild" has its roots in the German *biliðia*, which has long been translated into the Latin word *modulus*, but also is the roots of the word *image.* From this also the word *bildung* is derived, the word used for general education, since bildung, general education was to educate pupils to become like the teacher, or historically even like God.[22]

---

[22] Genesis 1:27 "So God created man in his own image", in Swedish: 1. Mos. 1:27 "Och Gud skapade människan till sin avbild"

7.2 Modelling in engineering versus modelling in education

> "Essentially, all models are wrong, but some are useful" (Box & Draper, 1987, p. 424)

Modelling is widely used in as well science as in engineering, and the main difference between science and engineering in that sense is the question of purpose. The main issue in engineering is to use it as a tool to analyze a dynamic system, and to predict the output from the system, before it is designed, e.g. to model a rocket and predict trajectories instead of making experiments, before it is built and launched. Of course many scientists would agree that this is also the purpose of modelling in science, but the explanatory power of a model is still predominant in science, and especially in science education: A model is used to explain the what and the how of scientific theories. Thus when starting to explain modelling in science, science education and philosophy of science, often the question of what a model is arises. One simple explanation could be: A model is an image, a representation of something and is usually used to make a simplification of something more complex. However, they can also be judged by *the work they do* (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003), or the "success rather than accuracy" (Knuuttila, 2011, p. 264). Interestingly "it was not until the beginning of the 2000s that representation as a specific topic of investigation began to interest philosophers of science" (ibid.). Yet, now that it is, still the question of representation is the most elaborated.[23] Knuuttila (ibid.) thus raises the question why representation was not discussed earlier although representations were widely used (she mentions pictures, photographs, numerical representations, tables, symbolic representations, among others), and answers that this was because the representational role of models had been neglected. But now that models are discussed as well as representations as tools there has been more focus on models as "epistemic tools" (ibid.) or "conceptual tools" (Bernhard, 2012). Another reason for models becoming a matter of academic debate is that models often are used in the interdisciplinary conversation, and although meant to facilitate the conversation the contrary is perceived. Gerlee and Lundh (2012) give two main reason for that: Scientists in different disciplines do not view models in the same ways, and they are not aware of their own views of models and modelling. In their book ”Scientific models: black boxes, red atoms and white lies”[24] they discuss models from different perspectives, (history and philosophy of science, art, etc.), and at the end show results from interviews they have made with scientists from different disciplines: hydrogeology, mathematics, climate research, marine technology, astronomy, zoology, organic chemistry, economics, neurology and statistics. The book is intended for university students with the aim to facilitate for students to appreciate models, engage in the interdisciplinary conversation, and inspire students modelling. The difference between this book and many articles on modelling is that they rather highlight the different views, than try to make a synthesis of what a model is or does. This is something that in my experience is what engineering and learning are about – to make choices of appropriate theories and models to design and to make holistic views from differences, respectively. Especially the issue of making choices on which models to use – which to take into account

---

[23] Cf. the chapter on philosophy of technology, where it is also stated that the questions concerning *technology as objects* is the most discussed item

[24] My translation of the title: "Vetenskapliga modeller: svarta lådor, röda atomer och vita lögner"

for which purposes? From the research in electrical engineering education, the works of Malmberg (2007) emphasises *phronesis* as choosing among knowledge from both the theory/model world, *episteme*, and the object/event world*, techné* (cf. chapter 5). The part/whole-relationship is at the core of Variation Theory and several examples of the whole/part relationships in learning can be found in the works of Marton and co-workers (e.g. (Marton & Booth, 1997; Marton & Morris, 2002a), and the capabilities that engineering students need to master is in this framework to learn how to choose among experiences, which include representations, mathematical tools, etc. (Bowden & Marton, 1998). This resonates well with how Haglund rephrases Duval, 2006, cited in Haglund (2012, p. 24): ”If children do not make such changes of representations, their mathematical knowledge remains compartmentalized and fragmented.” This *opening-up* is in my view of uttermost importance. Several authors speak of modelling or analogical reasoning as the way human beings naturally learn, as well learn about nature as learn to speak (among them Bowden & Marton, 1998; Gerlee & Lundh, 2012; Haglund, 2012; Knuuttila, 2011; Vince & Tiberghien, 2002). We register through our senses, compare to what we already have registered before, and choose among models to apply. Haglund (2012, p. 31) refers here to three different terms used in explaining why Artificial Intelligence cannot be mapped only through “representational aspects of structure-mapping” :“high-level perception” (Chalmers, French and Hofstadter, 1992, in Haglund, 2012, p. 31), “extended mind” (Clark & Chalmers, 1998) or “distributed cognition” (Hutchins, 1995). The dynamics of the modelling, and of learning gets lost when only recognizing the representational aspects. Neither philosophy of science nor models can neglect the knowledge in action: “Both the idea of ‘scientification’ and the attempt to let computers ‘take care of knowledge’ builds upon a philosophy of knowledge that recognizes the practice as solely a source of information for theory building and application.” (Molander, 1993, p. 39) Especially the point made by Knuuttila (2011) that viewing models as artefacts and not only as representations makes it possible to manipulate them, “play” with them, which according to her gives “epistemic productivity” (ibid., p. 269) and makes her call them, *epistemic tools.*

The most obvious models are the mathematical models, e.g. Ohm’s law: $U=R*I$. These are often taken for granted, and seldom discussed in the classroom, which has shown to be problematic for students entering science classrooms. Students use the mathematical models to try to explain concepts, e.g. they use Ohm’s law to explain that there cannot be voltage without current (González Sampayo, 2006) or voltage and current have to be in phase for an ideal AC-source regardless of the circuit connected to it (Kautz, 2011b). However, Ohm’s law can correctly interpreted, also help students answering these questions correctly – infinite resistance (open circuit), makes voltage without current possible, and using Ohm’s law (extended to include capacitors and inductors) together with Kirchhoff’s laws will render a phase difference between voltage and current if the whole circuit is considered, but if used in local reasoning, discussing only the voltage and current in one component, the students will come up with wrong answers. Thus to understand the models, and in which situations the models are applicable, i.e. which constraints that apply, is crucial. Some aspects of the disciplinary knowledge may only be accessible through a certain representation, and not at all possible to see in another, called “disciplinary affordances” Fredlund, Airey, and Linder

(2012, p. 658). It is also important to understand that these laws are models, and not explanations of “the truth about nature”. One of the questions (Gerlee & Lundh, 2012, p. 77) asked their group of scientists was “What is the difference between a theory and a model?”, and they received very different answers from their interviewees.

To just learn the formulae and to be able to manipulate them was formerly confused with conceptual understanding; throughout my own schooling, conceptual understanding was never asked for, whereas we today expect students to gain conceptual understanding. If the curriculum and the teaching are still the same, how can we possibly expect this to happen? Naturally research has shown that often conceptual understanding is not gained.

One strand of research on the nature of science (NOS) has been regarding the scientific method, and the whole idea of labs was introduced to make students engage in “the scientific method”. Although interesting and subject of a large body of research this will not be dealt with here. The other strand of research into learning of NOS has dealt with how to teach models and modelling, to make students understand what modelling is about, why we model, and what the benefits and limits of the models are. One such example is an activity designed by (Lederman & Lederman, n. d.), in which the main idea is to show that models are models, and may be refined, if found not to be “good enough”, and yet that they are models and not exact images, showing “the truth”. Several studies on how to learn to model have been carried out (see e.g. Brna et al., 2002; Redfors & Ryder, 2001).

One example of this is the COAST-group at Lyon2, who in several papers (e.g. Sensevy, Tiberghien, Santini, Laube, & Griggs, 2008; Andrée Tiberghien et al., 2009; Vince & Tiberghien, 2002) have shown how the process of modelling may facilitate for students as well to learn the nature of science as the specific topic at hand. However their modelling is not just a modelling of science, but also a modelling of how to learn science, which is not as common in science education. Even when researchers design tasks in which students are to learn to model, the nature of modelling is not made explicit. In all examples that the COAST-group at Lyon2 has modelled, they have considered the two worlds being the most important criteria in their modelling. In later papers they have also taken students’ own preconceptions, as well in the theory/model world as in the object/event world into account. Their modelling is thus threefold: The scientific modelling of the physics concept, the two worlds modelling of the concept to be learned and the modelling of students’ preconceptions in both worlds. By taking also the students’ preconceptions into account, they do not consider these prior conceptions as misconceptions, but rather “the learner constructs relations between a new element of knowledge and his/her prior elements of knowledge according to his/her overall understanding of the situation.” (Andrée Tiberghien et al., 2009, p. 2288)

This is very similar to the engineering view of modelling, and especially seeing “education as engineering” (Dewey, 1916) or “engineering education research as engineering” and “enigineering research” (Bernhard, 2013): Modelling is what engineers do, to paraphrase Mitcham’s discussion on design: “standard definitions of design do little more than rephrase the standard definitions of engineering itself” (Mitcham, 1994, p. 220). One of the most significant characteristics of models in engineering is that they are models of a *system*, and in descriptions of models this is clearly pointed out. In descriptions of scientific models, it is often expressed as a model of an *object* or a model of a *phenomenon*, which may or may not be a system. In engineering it is pointed out that a model is a *model of a system*, and the system is often also described. This is e.g. the case in a text book on modelling used in engineering education worldwide, which starts with the chapter: "Systems and models" (Ljung & Glad, 1994). One definition of a system formed by the society for General Systems Research (yearbook, 1964, cited in Ingelstam, 2002) is: "A system is a set of objects together with relationships between the objects and between their attributes." A somewhat more elaborated definition would also include that "they [these components] form some kind of *whole*…there has to be a *system limit*" and usually the system also interacts with "its *environment*" (Ingelstam, 2002 p. 19, my translation, italics in original). As well the parts-whole relationship, as the links between the parts are important aspects that always have to be modelled. Ljung and Glad (1994, p. 14) defines a model: "Loosely put, a model of a system is a tool we use to answer questions about the system without having to do an experiment". They recognize four types of models: mental models, verbal models, physical models and mathematical models. They define mathematical models: "the relationships between quantities (distances, currents, flows, unemployment, and so on) that can be observed in the system are described as mathematical relations in the model." (ibid., p. 15) and state: "Most laws of nature are mathematical models" (ibid.), which shows that in their view scientific laws are models. Above was mentioned that scientists from different disciplines hold different views of this question, and although Gerlee and Lundh (2012) interviewed very few scientists, and no conclusion on which views are more common, the different conceptions are there:

- "Hydrologist: The concepts [model and theory] are somewhat intertwined, as the hen and the egg. The model is a prerequisite for the theory, but maybe the theory is bigger.
- Mathematician: I am not so certain about this. I know what a theory in mathematics is, but e.g. in theory of relativity – in that case it is not a very big difference between model and theory, the way I see it. In social sciences theories are more far-reaching and sweeping.
- Climate researcher: Theories are, in my view, generalizations and synthesis of knowledges you have. Models are a way to test the theories, but also to create starting-points for theory development. Models are more like data or data acquisition, either in laboratories or in reality. Measurements and models are two complementary research methods. Theories are generalizations which draws upon both experimental measurements and modelling.
- Marine engineering researcher: Spontaneously I see models as narrower and more applied. But that can fit theories too, so I don't have a good answer to this.
- Astronomer: My spontaneous view is that models are something I use to build a theory. If it is a type of theory which I try to articulate, I need to use some different models as well to articulate the theory as to test it.

- Zoologist: Model feels more practical than a theory. A theory is something you want to prove and then you may use a model to do so. I do not view the model as a theory, but as a tool. Say that you have a theory of how the liver functions. How would you prove it? Well, you have to build a model.
- Organic chemist: A theory relies on knowledge, whereas a model is built from hypotheses for example we can build a model of a new protein with a desired property given known proteins. You could say that a theory is more underpinned than a model.
- Economist: Well, I would possibly spontaneously think that a theory is a more general notion than models. Theory is a broader concept. A theory may consist of several different models, but a model cannot consist of many theories. A theory is not necessarily a simplification of reality, which a model has to be.
- Neurologist: The models may be used to challenge the theories. You can challenge so convincing that finally you will have to rewrite the theories. So, in a way, the models test the theories.
- Statistician: In statistical theory there are lots of theorems, e.g. the central limit theorem. The whole theory building of statistics I built by formulating and proving theorems. But that has nothing to do with models. Statistical theory is solely built from abstractions, while models are only useful when they resemble reality."

  (Gerlee & Lundh, 2012, pp. 77-78, my translation)

The authors summarize their findings by:

"That models can be central to all disciplines despite the big differences, show the large span of the concept. Because, although you mean different things by the word 'model', there is still something that ties the uses together. Models give researchers access to a reality that almost always is too complicated to describe or change unless first simplified and abstracted, and thus be represented by something else. And it is in the very notion of a tool, that lets researchers come closer to the real world, where the meanings merge and the similarities become most evident." (ibid., p. 79)

That the idea of models as tools is the idea where the views merge is also in line with Knuuttila (2011, p. 267) who points to five characteristics that become highlighted by viewing models as tools: "(i) the *constrained design* of models, (ii) *non-transparancy* of the *representational means* by which they are constructed, (iii) their *result-orientedness*, (iv) their *concrete manipulability* and (v) the way *justification* is *distributed* so as to cover both the construction and the use of models." Models are constructed to" isolate some factors … and focus on their interrelationships" (ibid. p. 267) and different models have "different affordances as to how humans are able to understand them" (ibid., p. 268). She also points out that what distinguishes models from other representations is "their holistic *systemic* nature" (ibid.), which to me is a tautology since a model always models a system, as pointed out by Ljung and Glad: Models are used when measurements are "too expensive …, too dangerous… [or] the system does not (yet) exist" (Ljung & Glad, 1994, p. 14). To predict the behaviour of a system that is to be designed is one of the most important features of modelling in engineering, i.e. it is important to model the dynamics of the system. That it is the dynamics that is the most important issue in modelling in engineering is inferred by the names of courses and books in modelling in engineering – they are almost always called "model-building and simulation", where simulations always include variables that change with time.

The dynamic aspect of models seems to be rarely discussed in philosophy of science. However in the model described in this work the dynamics of students' actions has been very important to analyze, it is the change in students actions that is highlighted in this research. To model the relations between pieces of knowledge as links that students make, is to notice the dynamics of learning. Thanks to the dynamics it was possible to notice that all links were actions. That the pattern in the new course is different from the old course, is also possible due to the fact that a model can show the dynamics of the course of actions. I will come back to this in the discussion.

In modelling as well as interpreting models it is of uttermost importance to verify or validate the model, and especially the "*domain of validity*" (Ljung & Glad, 1994, p. 17). To know when to use a model, what limits there are, etc. is very important. One example often mentioned to exemplify what is meant by this is Newtonian mechanics, a model which is valid for most moving objects, but only when speeds are far from the speed of light.

In the text book "Modeling of Dynamic Systems", Ljung and Glad (1994) identify two different ways to model: physical modelling and systems identification. One of them starts with physical laws, and the modelled behaviour of a complex system is derived by combination of known models of simple systems. The other starts by data from measurements where parameters are identified e.g. from transient response, or frequency response without bothering about the model being representing every variable that possibly may vary. For simple systems the physical and the identified models often become the same, e.g. for a simple DC-motor. However, for larger systems this is usually not be the case, but the graphs retrieved by simulation of the two models will look the same, the dynamic behaviour of the two models will be the same and thus they are considered equally valid. Again this resembles the discussion by Knuuttila, that the most important feature of a model is not to represent, but to be a tool for analysis.

The modelling in engineering is used as an epistemic tool, but also as a design-tool. Thus design and modelling share many of their methods. Above Mitcham and Tiberghien were mentioned, and both of them speak of designing a model, rather than modelling, to emphasize that *modelling is to design*. To design lab-instructions or teaching modules is to design, and to do research on this kind of design is to carry out design-based research, which Tiberghien points out by the title of her latest article: "Design-based research: Case of a teaching sequence on mechanics" (Tiberghien 2009). In such engineering areas as Enterprise-Modelling, also design-based research or design science research form the theoretical framework (cf. e.g. Banafshe 2013). Thus engineering education research is as well engineering as engineering research (Bernhard, 2013).

One aspect of modelling is to use the modelling process itself as a tool of communication. This is emphasized throughout the book "The role of communication in learning to model" (Brna et al., 2002). The title could as well have been the role of modelling in communication. It is as well the model as a tool as the modelling process as a tool. Whether modelling and models are tools for communication or communication is a tool in modelling is a hen-egg discussion, however all three are used as epistemic tools to facilitate learning.

Also research is a kind of learning and to model what students do is for an engineering education researcher a tool to learn about students' learning. As an engineer, entering engineering research it was at first a tacit choice to model the object of learning, especially since the object of learning here was a complex concept, consisting of many parts where the relationships were not fully elaborated. Although tacit at the beginning, it has been possible to communicate through the model and by describing the modelling process.

7.3 The theory-practice divide

Both in the chapter on previous research and in the above chapter on modelling the question about the theory-practice divide appears. In a seminal paper on modelling in physics education, (Hestenes, 1987) discusses what modelling in science and modelling in education need to be in order for students to learn. He describes the modelling process in four distinct stages, where the first is the "object description" and the second is "formulation stage". After both of these the object model, including the dynamics of the physical object are modelled. The next two stages, "ramification" and "validation" deal with the process of modelling the scientific method. This recognition of two different processes, firstly the dynamics of the physical object or physical concept, secondly the dynamics of conceptualising the object. Here he shows that e.g. electric circuit theory is a mathematical model, but what usually is called "apply it" is a modelling process. Although referring to this article sometimes this double modelling procedure is not recognized, as it is in the works of e.g. Andrée Tiberghien et al. (2009). Instead the division Hestenes (1987) makes between factual and procedural knowledge has drawn researchers attention and led to a debate about factual and procedural knowledge.

That theoretical knowledge put into practice is another kind of knowledge than procedural knowledge is recognized by Ryegård (2004) and Thuné and Eckerdal (2009), but they keep the divide theory-practice. Tiberghien (2000) on the other hand chooses to make another divide, the divide between the two worlds theory/model world and object/event world. The benefit of this is twofold. Firstly the dynamics of the model within the theory/model and the procedures of modelling, making a model from the object/event world are clearly separated. Secondly the very word practice is problematic. Sometimes we do distinguish between the words practice and praxis, as in rehearsal and e.g. medical practice, where the first one means only the procedural aspect and the other the whole enterprise including the rooms, people, equipment and of course know-how. This has been vividly debated in philosophy of knowledge, with seminal texts written by Schön (1983), (Polanyi, 1967) and (Molander, 1993), with discussions on "tacit knowledge".

I will return to the problems as well with the divide *per se* as choosing a specific terminology in the discussion.

7.4 The procedure

To learn a complex concept it is necessary to recognize and understand as well the concepts involved, what to do, and how to relate the concepts to each other and reflect on the whole in variation-theory is expressed as: “learning is about coming to understand something of importance in a way that is qualitatively more in line with desired goals, and that this is a matter of expanding awareness to embrace greater wholes, more parts within the wholes, and stronger relations between parts.“ (Booth, 2004, p. 13)

In order to find the critical aspects through modelling the object of learning, the model needs to display as well the parts as the whole. However, since critical aspects are often taken for granted by teachers, it is important that the model reveal these taken for granted. Hence, starting with the model by Tiberghien and co-workers, we looked at what students were doing in labs, what aspects they were dealing with, and which paths their meaning-making took. We saw that sometimes they were only dealing with one concept at a time, sometimes they were relating different concepts to each other. Drawing a figure from this we achieved our model

The object of learning, when working with the Laplace transform to solve the differential equations, is to learn and reflect on the chain from the real circuit through the mathematics onto the graph derived mathematically, to compare this graph with the measured graph and thus relate back to the real circuit again.

To begin with, the concepts to be taught, were listed in a similar way as they were presented in text books, i.e. a commonly agreed upon curriculum: the drawing of the circuit, the real circuit, the measured graph, the mathematics needed – the differential equations, the Laplace transform and its inverse transform. Very seldom the calculated graph is considered a concept of its own, neither in mathematics courses nor in the text books. If the calculated graph is drawn, it is to show the concepts “critically damped”, “underdamped” and “overdamped”, which are the three possible kinds of curves also described in the appendix. One exception is the text book: “The analysis & design of Linear Circuits”, by Thomas, Rosa, and Toussaint (2012, pp. 353, 358, 363 etc.).

In our model we have chosen to let the calculated and the measured graphs be considered as two different concepts. We did so for two reasons: the students did not consider them to be the same, and actually, the very task of the lab is to make a curve fit, i.e. to draw a theoretically derived curve, which looks as the measured curve, in the same graph.

The list of concepts were then drawn as circles, but the circuit diagram and the physical circuit were considered as being one concept. Earlier in the same course these two would be drawn as two separate circles, but in this lab they have merged into one concept: the real circuit.

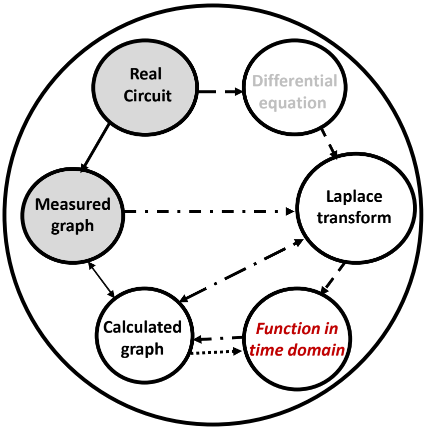


Figure 13: Example of how the model can appear at a specific point in a lab. Here when the students ask what type of curve is possible (function in time domain) and the teacher answers: by use of the Laplace transform.

The two shaded circles are concepts from the object/event world, and all the other are from the theory/model world, adopted from Tiberghien (2000). In lectures the teacher has followed the circle from the real circuit, through the differential equation and worked examples dealing with the Laplace transform and its inverse transform, thus the dashed arrows between the circles. When analyzing the questions students raise and the answers the teachers give, the dash-dotted arrows could be derived, and following what the students do, the solid arrows could be derived.

The students start by connecting the circuit-board to the connectors output voltage and voltage sensor. The question "Connect over the whole circuit" (see chapter 8.1.1) and "What is a step response" (see chapter 8.1.2) are both questions concerning the arrow between the "real circuit" and the "measured graph". At this point of the lab the established links may be illustrated by the figure below:

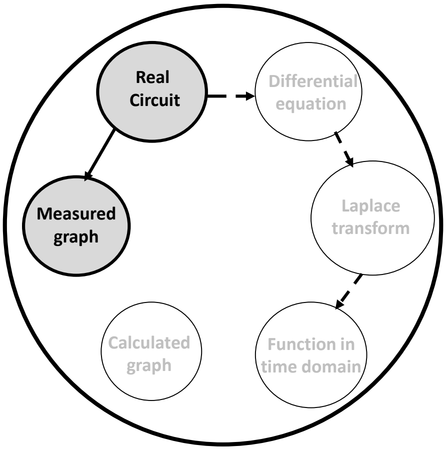


Figure 14: Modelling the established link between the real circuit and the measured graph

Again the dashed lines are what the teacher has lectured about and worked examples concerning. The students are satisfied with the answers, and are able to go on, the gaps are filled, and the arrow between the real circuit and the measured graph can be noticed, and thus drawn as a solid arrow.

During the elaboration of the graphs, the students first work with a given time function. They still ask if they are supposed to use the function given in the instruction, and the teacher answers that in this case it is that formula, but that the task also is to find out which other function or functions that may be useful. They wonder how they may find out, and the teacher says that it is necessary to obtain the transfer function by means of the Laplace transform and use the poles to figure out which time function to use, implying either a damped sine wave or two exponential equations. The dialogue from chapter 8.1.3.2 (2002_Group_13 _Tape_2 4:37 ff.) can be illustrated by the following figure:

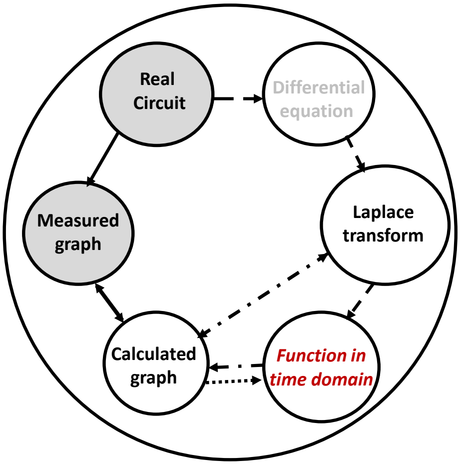


Figure 15: Modelling the conversation between the students and the teacher, were the teacher tries to make the students notice the importance of linking the "function in time domain" to the graphs in order to decide which function to use for the curve fit.

Here the teachers answers form a triangle of dash-dotted arrows from the calculated graph, which is to be obtained, the Laplace transform and the inverse transform to calculate the graph, and the students question as a solid arrow. The "function in time domain" is marked with red italics, since it is the central concept in question, although the students are not yet grasping what to do.

A couple of hours later the students get help from another group, who have carried out the tedious calculations, and at the end the figure may be drawn as follows:

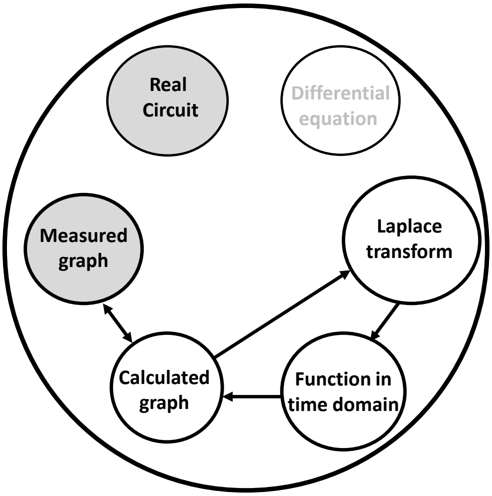


Figure 16:The model of established links a couple of hours later, when results from calculations are available.

The figure shows that the student who has done the calculations now followed the path from the calculated graph to the Laplace transform and via the inverse transform back to the calculated graph, whereas the other student still was working on the arrow between the measured and the calculated graph. At the end of the lab, satisified with the curve fit, they are still not satisfied with their understanding of the lab:

```
2002_Group_13 _Tape_4 25:10 (ca 2hours 45 minutes)
Jack:  Now this doesn't work at all.               George leaves
       I'm tired of all this testing               Jack leaves
```

They have still not merged the parts described by the model into the whole concept "Transient response"

In the next section, the results from following the procedure above, through the questions the students posed during the labs, will show how this procedure was carried out in order to model the object of learning. The dash-dotted lines and the solid will not be separated, but all arrows will be drawn as solid lines. This was a deliberate choice, since trying to make a model too detailed, will make it "no longer a model but the object itself". A model is always a reduction of detail, else it is not a model

8 Results

This chapter comprises four different studies, although stemming from the same data set. It could have been divided into four separate chapters, or as is common in a thesis into four research papers. In that case the studies would have been presented in another order, the order in which they were carried out. Here, however, I have chosen to present them as one chapter in an order which makes the model and the possible future use of the model more comprehensible.

The chronological order of the studies was: analysis of the old course, analysis of changes of the lab-instructions, the new discourse and finally, the analysis of reasons for the change in discourse.

However, to make the model more useful for someone to use as a tool, the order in which the studies are presented here is possibly more relevant:

- Find out what students do or do not do by studying their questions in the lab-situation, and draw a preliminary model of the object of learning
- Analyze the links – as well those made as those intended, especially concerning the divide between the two worlds
- Make changes to the curriculum or instructions
- Test the relevance of the changes made

The problem with video-data is that it renders many hours of data to analyse, and especially long passages without anything to analyse, or maybe long passages where nothing seems to happen and still there could be something that is missed. One way to handle this problem is to look for passages where students pose questions to the teacher, and study also the moments shortly before and after these questions: What questions are raised? What kind of answers do the teachers give? This is one way to study students *practical epistemologies*. Thus the first part of the results-chapter will be *What questions are raised during lab-work?*

The study of such questions and questions still lingering, resulted in our model that made it possible to analyse video data in a much more efficient way.

A model always needs to be validated, and validating a model amounts to analyze it in different ways, and evaluate the consistency of the results gained. In the chapter *make links* the model is analysed by investigation of the links students make. This chapter will show how the model was used as well in analysis of what the students do during lab-work as in analysis of *critical aspects*, i.e. what should be changed in the lab-instructions and teaching in order to enhance the *enacted object of learning*.

The new *task structure* lead to a new discourse. Here two different strands will be discussed, the changes in the lab-instructions and the changes in the setting of the lab sessions. The instructions have been changed according to *Variation theory*, and the setting of the lab session as *integrated problem-solving labs* in order for students to cope with tedious calculations, will be made as a discussion related to *Threshold concepts theory*.

The chapter ends with an analysis of the *new discourse*, the *new enacted object of learning*

8.1 What questions are raised during Lab-work?

The questions raised during lab-work can be seen as the *gaps that students notice,* gaps between what students consider *standing fast* and a new *encounter.* Thus a way to study students practical epistemologies can be to study these questions. What kind of questions occur?, Do the students fill the gaps or are these lingering gaps? This section will study the questions in order of appearance in the lab before the changes were made, i.e. the course 2002. It will describe how different groups ask the same or similar questions, but also whether some questions are unique. The teachers are John and Anna.

8.1.1 “What does ‘Connect across the whole circuit’ mean?

The first question that may occur is about the wiring of the circuit: “What does ‘Connect across the whole circuit’ mean?” It is read from the lab-instructions, and concerns where to connect and measure the input voltage. Group 13 asks this question, and the following discussion is recorded:

```
2002_Group_13_Tape1_00:11:47
Jack: John!
John: Yea                                  Comes to the group
Jack: What does this mean ‘Connect across
       the whole circuit’
John: what
Jack: It says connect the output across the
       whole circuit
John: Well, the you should =
Jack: = How do you do that
John: Then you have in and outputs where
       you should have one if you have an
       RLC-circuit then for example if you
       include the 10Ω-resistor, then this
       is across the whole circuit
                                           Shows by connecting
Jack: OK, it was a little cryptical, hard
       to understand which one to use
John: There was a headline that
Jack: Yea, it said that we shouldn’t use
       this one
John: No, not in the first one, there are
       others
```

```
Jack: But this one is connected here
                                           Points at the 10Ω-
                                           resistor
John: No, no if this is the first step,
      you should is it only this one then
      we have the R in this=               Points at the inductor
      Here the R should be the
      internal R in the inductor

(Jack cuts off John when he knows which R to use:)

Jack: =‘Voltage sensor’ is this one also
      to be connected across=
John: = No that one that one you should
      connect across the capacitor
Jack: This is rather difficult
(4s)
John: But it says in the instruction
      RLC-circuit
Jack: Mm
John: R L and C
Jack: Yea, but where do we connect         Looks around for John who
                                           walked away
(10s)
John: But it says in the instruction you
      should (.) capacitor (.) voltage sensor
(1s)
Jack: So this one is supposed to be across
      the capacitor
John: Yea, it says in the text
(10s)
(John tries to find the text John is referring to)
John: Well it is easier to =
Jack: =(doesn’t listen any longer) First measurement
```

Although the teacher’s statements are rather rudimentary, the students understand from the actions what to do, and how to interpret the not particularly clear text, and can now go on.

Here two problems are revealed, one is that the expression “connect across the whole circuit” is not immediately understood, but also the confusion that in the very first measurement the *R* is not an explicit *R*, but the internal in the inductor, whereas in the rest of the measurements the students are expected to use different values of *R*, and the *R* is a separate component. It seems that the teacher John does not notice that the question raised by Joe and Jack is considering which *R* to use rather than how to connect when they know which *R* to use.

There is one more issue that may be a problem and that is that “output voltage” on the computer interface, is the output from the interface, which is the “input voltage” to the circuit, thus confusing expressions occur. Groups 14 and 21, did not notice the expression “over the whole circuit” which leaves a lingering gap in their understanding of how to connect this voltage when reading the lab instructions. They try to connect, but need help. Both groups have connected the input voltage (the connector called “output voltage on the interface”) to only the capacitor, not “across the whole” circuit. The teacher helps them to connect, and tells them that the input should be “across the whole circuit” and the output across the capacitor. Even with this help group 14 does not measure both input and output, but only “output voltage” from the interface, for another five minutes.

The other groups manage to resolve this problem without asking the teachers, but a couple of groups discuss the fact that they use the equipment too seldom

8.1.2 “what is the step response”

A question raised in most groups is “what is the step response?”. This should be known from lectures, but since a single step is difficult to measure, the most common way to obtain a step in labs is to let the input to the circuit be a square wave, and let a rising edge be represent a step input, and the output be the step response. This is not trivial. In the instruction it is asked that the students choose square wave early in the lab (p. 4), but that this will render a “step” is not mentioned there. Two pages later (p. 6) the students should have received an output signal from the circuit when a square wave is the input signal, and they are asked to “rescale the graph in order to retrieve the step response itself” (Swedish: “Denna figur kan nu skalas om för att få fram själva “stegsvaret”). Indicated by the word “itself” (or maybe a better translation would be “as is”) the teacher tries to convey that it is a model of the step response, modelled by repeated steps, i.e. the square wave, and not just one step (one single transient), but in the answers to the students this is not always explicit.

When group 11 asks this the first time 00:02:55, the teacher answers by just rescaling the curves (the input and output from the circuit) and tells the students to keep the curves synchronised. He leaves, and they ask again at 00:03:47:

```
Anne: retrieve the step response itself (.)
      I don’t understand
Beth: the step response (slowly)
(3s)
Beth: This is the step response           looks at the screen,
                                          turns her head
Beth: But, what is it supposed to look like
Anne reads in the instructions mumbling
Beth: What does this mean?
Anne: I don’t understand what he means by
      the step response
Beth: But even if we would understand what
      he means, what would we do with it
      anyway? What have we done?
(8s)
Anne: Is it exactly here, where it goes
```

```
      down that we shall
(2s)
Beth: It looks as a (.) Noo, I don’t think it ..
(4s)
Anne: Bu’, what’s the meaning of a step
      response?
00:04:49
Anne: John, come here a second!
John: yea
Anne: What do you mean by ‘the step
      response itself’?
John: It is the output that you get       points at the screen
```

Again there is no explicit explanation of what the step response is, but the students settle with the answer since they now know how to go on with the measurements.

8.1.3 Elaboration – make a curve fit

Some groups start with the curve fit already when measuring the first curve, others have not noticed that this is the main task in the lab, thus they do all the measurement on all circuits first, and make the curve fit later on in the lab. In the instructions the program to work with is rather thoroughly described (4 pages). After this about one page is dedicated to the first measurement. A short section describing the following measurements, only seven lines, comes next. The last section is on how to elaborate the data, to make a curve fit, i.e. to make a calculated graph and the measured graph fit. In the instruction this is described for the first measurement: use “user defined fit”, define your function, change values a,b,c and d until the curves look alike, use these values to calculate the values of *R*, *L* and *C* in the circuit, compare these with the actual components. Only one function is given: the function for a damped sinusoidal curve, but it is stated that there may be a need to use another function at the end of the section: “Note that depending on the value of *R*, the suitable function to fit to will be different.”[25]

8.1.3.1 Group 11

Group 11 has started to make measurements, and after about a quarter of an hour they wonder what the purpose of this task is. They study the instructions thoroughly, but stop at the point where they read:

```
2002_Group_11 _Tape_1 17:18
Anne: Here it says: "Your task is to
      make fittings to the graph
      showing the measured current,
      when L and C are kept constant
(20 s)
                                          Anne looks at the
                                          instructions
```

---

[25] ”Observera att beroende på vilket värde som R har så kommer lämplig funktion att anpassa till att vara olika”

and the lab board alternately
Anne: Is that what we have done? Reviews her notes from the measurements
(30 s)
Anne: I don't understand
(5s)
Betty: Let's start with one, then
Anne: We are to add some kind of curve onto the other onto those we have saved, that is. OK, it's just to do it Turns to the page where settings for the measurements begin
Betty: Mm
Anne: Let's open the first one then.

They start with the first. They open the user defined fit, but have not entered any function, so they get a straight line at zero. They ask teacher 1 if this is the right curve. He reenters the curve fit (not looking at their window), and he shows them how to receive only one step (which they did not ask), by doing it for them, and after that he tells them to enter the function. He then walks away. They are back at the same point as before the teacher came, so the gap is still not filled.

2002_Group_11 _Tape_1 24:39
Anne: Are we supposed to calculate it first
Betty: But we have no idea about what formula this is
(30s)
Anne: Do you think this is the formula to put in
Betty: But it is hardly so, We probably have something different, other parameters
Betty starts to add the function which is in the instructions, Anne looks around. Teacher 1 comes up to them:

26:39
Anne: Mister, this formula here, is this the one we should enter? Points to the instruction
John: Yeah, it is is it is
Anne: Is it exactly this one or what is it?
John: It is a damped sine now yes, it is this one then, it looks like a damped sine, but then it generally concerns then what formula it is supposed to be
Anne: And one is supposed to know that?

Betty: But that's difficult to know
John: What did you say
Betty: But how do you know?
John: Yeah, but you get a tip from
calculating the current as a
function of R, which gives you
different kinds of poles.
(4s)
Betty: I don't understand
John: If you express the current by means
of the Laplace transform

The discussion goes on for another minute or so, but ends with Anne's question:

2002_Group_11 _Tape_1 28:15
Anne: But are we supposed to enter this
one
John: Yes
T1 leaves

Again here is a lingering gap. The students did not make any relations to what they had learned in the lectures or problem solving sessions, but again repeated the very same question as they had started this conversation with. They again get the straight line, and ask the teacher why. He explains that they need to try to find out what the parameters mean. He also talks about the internal resistance in the inductor, something they didn't ask for, and this is ignored by the students. They now start to explore the parameters and find the best fit within 20 minutes.

Next graph is not obviously a damped sine, which the students discuss, but since they cannot find out what kind of curve it might be instead, they try to fit a damped sine again. It takes about 20 minutes, and when they are satisfied they ask the teacher to come:

2002_Group_11 _Tape_2 36:16
Anne: We can't get it any better now
John: No, which one are you doing
Anne: We are doing the one with the
10Ω resistance
John: 10Ω
Anne: It is if we change here, but then
some change occurs there
John: Yeah, but that may be due to the
zero there
Anne: But is it OK?

After this they discuss if they should carry out some calculations, but decide to postpone that. They start their third measurement. After a couple of minutes:

2002_Group_11 _Tape_3 5:19
Anne: This is the hard thing, one doesn't
understand anything
Betty: No, exactly
Anne: Do you find this to be a damped sine?
(Both start to laugh)
Betty: Yes!
Anne: No, it can't be

They discuss the differences between this new curve and the old ones, especially the “sharp peak” at the top of the curve. They still try to fit it with a damped sine, return twice to the “sharp peak”. After about a quarter of an hour they ask the teacher about their problems:

2002_Group_11 _Tape_3 17:19
Betty: It looks so strange
Anne: Yes, it does
John: Which one are you doing
Anne: R33
John: Is it obvious that it is a damped sine
Anne: No, but we didn't have any other guess.
John: What alternatives are there?
Anne: We don't know

After a couple of minutes they have come to the conclusion that it is two exponential functions added. For 10 minutes they are now using trial and error to make the curve look somewhat like the measured graph. They change the parameters randomly. Between each statement they make, there is a 2-3s pause. But suddenly they get something more like the graph, they also found out that *a* and *c* are of opposite signs. From now the conversation changes and the testing is not random any more. Still they don't get the right curve, and they ask the teacher for more help. He asks if they have done any calculations yet, which they have not. First they say to him that they will do that later, but he insists that they should do some calculations now, in order to find out what kind of values that may be possible, e.g. *a* and *c* are of opposite signs, and also that both *b* and *d* have to be negative.

After 2½ hours they have done the calculations on the third example together with another group, and also received a satisfactory curve fit to both the third and the fourth graphs. Betty reviews their saved material, and Anne continues to do some more calculations, but leaves here place after a while, which results in video-recordings without conversations. They leave after 3:45.

8.1.3.2 Group 13

Group 13 starts with questions about how to connect and also about which kind of signal to use as input. After a short while they start making measurements, and save the graphs from measurements using $R_{inductor}$, R_{10} and R_{33}. After about 40 minutes students from another group ask this group whether they have done any fittings of the curves, which they have not. They review the lab instructions, and utter:

2002_Group_13 _Tape_2 0:06
0:06 Jack:What the h_ are we doing?
1:54 Jack:But what curve fit.
Are you supposed to just test it

Some minutes later

2002_Group_13 _Tape_2 4:37

Jack:	This is not at all like theirs	turns towards the teacher
	This is just a bunch of errors	loudly across the room
	Now he´s gonna have to explain	
	for once	
(Silence until teacher John comes)		
George:	We've done this	
Jack:	We've opened a user defined	looks towards the screen

(The teacher shows how to open the right window (the conversation is almost inaudible) Continues at 6:34:)

John:	So now you can continue	
Jack:	But we got error there too	
John:	But you haven't defined anything yet	
Jack:	But what am I supposed to define then?	
John:	But it tells in the instruction	
Jack:	And we were supposed to understand this?	
John:	Mm, Now it is about unders' now	
	you have got a function an' then it's	
	jus'to (.) well it's measurements	
	that you're to try to model	
	mathematically an' it is ab' try	
	to recognize what it is can be which	
	function it is	
Jack:	Well, I wouldn't have guessed that one	
John:	Hmm now you are on another one	refers to R_{ind} and the students measured R_{33}
(Jack, George and John say something simultaneously)		
John:	Like that damped one it is most obvious	
	in the first measurement	
Jack:	=Mm	
John	=with the inductor then for the other	
	also it is then to (.) think about	
	what (.) what it is can be which type	
	of function. You can also find out	
	which function it is by looking at the	
	Laplace Transform of the current and	
Jack:	=Mm	

```
John:  =the poles are
Jack:  Now this became all too advanced.
       I would never have figured that out
(John leaves, George browses the instruction and Jack giggles)
Jack:  Alright, let's Laplace-transform
       an check the pole-values then.
Jack:  We have to make some small adjustments
       to make them fit and to do that one
       uses the Laplacetransform and finds the poles.
```

This last quote is reoccurring at least three more times during the lab:

```
2002_Group_13 _Tape_2 13:03
Jack:  We have to make some small adjustments
       to make them fit and to do that you
       use the Laplacetransform and find the poles.

2002_Group_13 _Tape_2 14:37
Jack:  let's run the Laplace-transform and
       check the poles, hey.               ironically

2002_Group_13 _Tape_3 15:50
Jack: I am doing the poles here
```

The first three times this quote can be considered a lingering gap. The students do not know what to do or how "doing the Laplacetransform" is going to help, but they notice that this is important. The last quote (which appears 45 minutes later, tape 3 15:50) shows that Jack has realized that he has to do the calculations, and when he has done so this quote is not repeated any more throughout the whole lab. After calculations are carried out, the group has filled this gap. Another statement that Jack has said several times throughout the lab is

```
Jack: this is all random for trial and error26
```

They ask for help once more and the tip is to try to figure out which parameter changes what, and they try to find the relation between the constants *a, b, c* and *d* and the real world, i.e. *c* stands for the frequency of the sinewave, *a* is the amplitude, and *b* the damping. But, again the students fail. They start with parameter *b*, which they have found to be the damping, but since they use too low frequency the curve seems to "jump" randomly when they try to change parameter *a*. Again they ask for help and they find it easier to start with parameter *c*, which easily can be calculated by measuring the period of the sinusoidal oscillation.

The first task, to fit the first curve, was thus finished after about two hours of the lab-session. During this last half hour Jack has also started to do some calculations. By the time Jack has finished the calculations of the poles for the first transfer function, George has fitted the second curve after about 2½ hours.

---

[26] The qoute is a ”home made” expression (Swedish: ”Detta är random för trial annd error”)

When they come back to curve three again they still consider it to be a damped sine, but there is no possibility to make the curve fit to the function. They ask the group next to them and ask about what value they have for *a, b, c* and *d*, they tell their values:

```
2002_Group_13 _Tape_4 25:10 (ca 2hours 45 minutes)
George:   But there we ought to have 4000
Jack:     No, maybe not, 'cause this isn't
          complex like last time.
Charles:  No, that's right
Jack:     Here we just have ordinary
David:    You have to change the function, you know.
Charles:  You can't use the sine on that one because=
Jack:     =then it will just be two e:s, won't it
```

They change the formula and the fitting is finished after about three hours. The fourth curve is done in just some few minutes, but now the two groups work together. They continue with some calculations, check if they have saved all the graphs that are needed for the report. The extra task was to look at the change of the curve if an iron core would be inserted into the inductor. They work with the curve fit for a while but conclude (after 3½ hours):

```
2002_Group_13 _Tape_4 25:10 (ca 2hours 45 minutes)
Jack: Now this doesn't work at all.             George leaves
      I'm tired of all this testing             Jack leaves
```

8.2 Make links

Already when *the model of a complex concept* (see figure below) was formed it was obvious that the links between the islands were not just there to learn, but that the students had to “make links”, create ways to pass from one island to another. It is, therefore, important to clarify the nature of these links, both in terms of the concepts/relationships in which they are incorporated and the concepts they link. In engineering education the concepts taught are mostly complex, and some links transcend one world while others belong within a single world. In order to map and elucidate these links, and enable them to be highlighted in the lab-instructions, a thorough analysis of our extended model showing all of the links, and whether they belong to one of the worlds or connect them is required.

In order to illustrate the links each figure below will be the full model of the intended object of learning, with all links drawn, but with the one discussed highlighted in red

One of the links is to calculate the transfer function for a given circuit. This could be considered as “just something to learn”, but what does it mean to learn this? Molander (1993) gives a similar example: “mass is energy”, and claims about this and similar statements that : “it is obvious that there is no *knowledge* in the *statements themselves*, there is something to know only if one *understands* the included *concepts* and the *activitycontext* where they belong.”(p. 61, my translation, italics in original) The learning process is *in* the action .

To create links is also to be aware of more than one *island* at the same time; to *make links* is to keep more than one *island* in *focal awareness simultaneously*, which according to *variation theory* is a necessary condition for learning. The model became a way to see what students had in focal awareness, while working with the tasks. But the model also became a way to see what students did not do, what concepts they worked with in isolation, i.e. what links they did not make. When they *made links* it was possible for the students to go on with the task, while when they did not make links, but focused on only one island, *single island*, at a time, the students were not able to go on with the task, and were thus hindered in as well the task itself and hindered in the learning process.

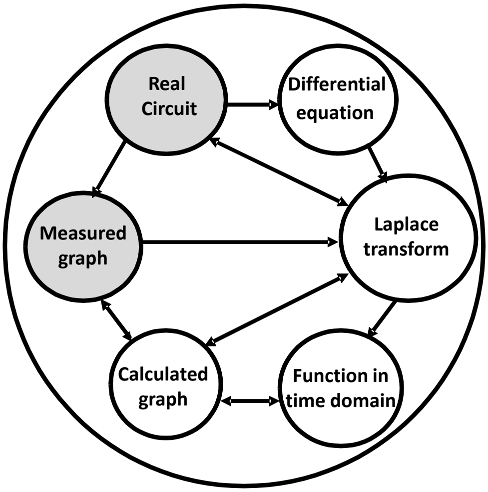


Figure 17: The model of the learning of the complex concept, transient response showing the intended object of learning, i.e. with all intended links marked as arrows and concepts to learn drawn as nodes or islands

Following the circumference of the circle, the links are the following. One link is from the real circuit to the differential equation. This link consists of the mathematical modelling of the physical properties. The next one consists of deriving the Laplace transform from the differential equation, which gives the transfer function. The next one is to do the inverse transform in order to get the time function (which in the first versions of the model was named "inverse transform" although it ought to be called "time function"). From that to the calculated graph the link is to draw the graph. The next link is to associate the measured and calculated graphs by means of expressions like frequency, amplitude, damping. The link from the circuit to the measured graph, is to do the measurements by a connected computer interface. In order to extend the parts-whole-relationship to include more islands in focal awareness simultaneously, one way could be to establish links across the circuit, e.g. directly from the circuit to the transfer function, and in the new course also a direct link from the transfer function to the calculated graph is made possible through simulations.

The links are thus different, but all of them *consists of something*, something *to do*, or *make*. Something that also *gives* the relation between two *islands of knowledge* – or *concepts*. There is something for the students *to do*, *to grasp*, *to make*, more than just *to associate*, *learn about* or *relate to*.

The model was at first a result from the analysis of the video-recordings. As we listened to the students we could notice what they were talking about, which gave us as well the islands, which concepts they were dealing with, as the routes they took going from one task to another, the arrows in the model. We found that this tool was useful in analyzing what students were doing. It showed how the parts-whole-relationship was enacted, whether or not students were working with one or more concepts at a time. But when writing about the model and the learning the model was aiming at describing, the arrows, the relationships, the links seemed to be more than just a route of actions.

This chapter will explore each of the links in terms of what learning each arrow, each link represents. The links are explored in terms of what learning is made possible through the lab instructions, and what the changes in instructions opened up for. A short reflection on the appreciation of links as actions, will end this chapter. A discussion on implications for learning will be given in chapter 1.

8.2.1 The link from real circuit to differential equation and onto the transfer function

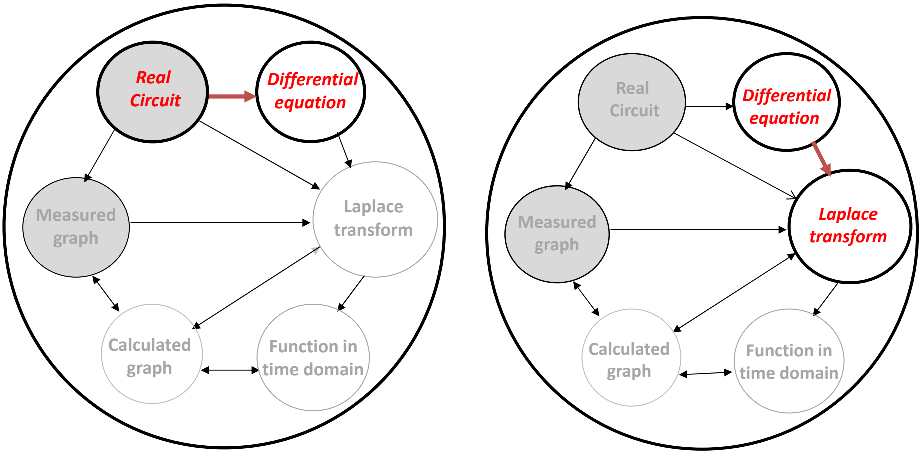


Figure 18: The two links made in lectures. a) Mathematical modelling and b) Calculating the Laplace Transform

The link from the real circuit to the differential equation is a modelling procedure, making a mathematical model from physical experience, in this lab not very much elaborated, although discussed in other papers (e.g., Bernhard & Carstensen, 2002; Hestenes, 1992; Roth, 1995; Andree Tiberghien, 1998; Andree Tiberghien, Jacques Vince, & Pierre Gaidioz, 2009; Vince & Tiberghien, 2002)

In the course 2002 this modelling procedure is only carried out in lectures and problem-solving sessions, and not a specific task in the lab, and thus such data could not be obtained. However, in the text book (Nilsson & Riedel, 2001) it is presented. It is also introduced in another lab, where the steps to go from the circuit onto the differential equation and further to the transformation of the expression by means of the Laplace transform is done as mathematical manipulations.

8.2.2 The link from the transfer function to the time domain

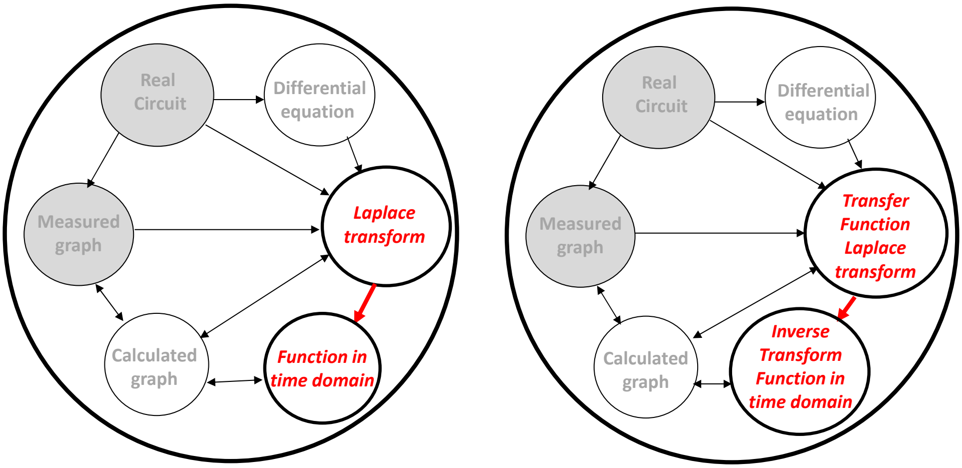


Figure 19:The link from the transfer function (Laplace expression) to the inverse transformed function in the time domain. b) possible suggestion of revision of the model after analysis of this specific link

In the very first description of the *circle* representing *the object of learning* in the transient lab *the island* between *the transfer function* and *the calculated graph* was called *inverse transform*, since it was the time function that the calculated graph should show, and the route from the transfer function to the graph is to do the inverse transform to obtain the time function. This reveals two questions: 1) If it was just a route, a link between the transfer function and the calculated graph, why would it be *an island* of its own? Or put in another way: If it is *an island* why is it not expressing a result? 2) Why was it not obvious to the researchers that *the islands* had to be *results* and *the arrows* had to be something *to do*.

Reflecting on the first question, it is only possible to go directly from the transfer function to the calculated graph by means of computer simulations. By hand the inverse transform renders a time function as its result, and thereafter, the calculated graph can be drawn. In the computer program that the students use, Datastudio, they have the possibility to draw their own curves in the same graph window as they get the measured graph, they make a *curve fit*, where they choose a user defined graph, which is the time function. So the short answer to the first question is that the island was necessary, and it is just a matter of choosing the right label, to name the *island time function* instead of *inverse transform*.

Noting that the island now has a noun as the name, the time function, which is the result of an action rather than the action, makes it possible to notice that all islands have nouns as their names, and that all links represent something *to do*. The answer to the second question is thus, that the choice of a faulty label made it possible to notice, to become aware that *all islands are nouns and all links are activities*.[27]

Seeing that the transformed function (the transfer function) and the inversely transformed function (the time function) are nouns and thus islands, while the transformations are links is thus an important learning for the teachers and researchers. However, this also makes it possible to notice that the links are not just to manipulate mathematical routines, but also to keep these two concepts (or islands) in *focal awareness (Marton & Booth, 1997 especially chapter 5-6)*, while as well comparing results in the Laplace domain and in the time domain, as in going between them. If it were just to learn the links, the manipulations would be enough to learn, but since it implies keeping both domains ***and their relation*** in focal awareness simultaneously, it is a link that has to be worked out by the students themselves. Talking in terms of *Threshold concepts* to just do the manipulations would be a type of mimicry, whereas keeping the relationship in focal awareness simultaneously, while studying the time functions, the transfer functions or carrying out the transformations, is to have passed through the portal. In phenomenographical terms it would be considered as *seeing the object of learning in a new way*, having reached a *deeper understanding*, and to be able to give a more *complex explanation*.

---

[27] The same could be said about the transfer function; it is called Laplace transform in the model. Also the expression Laplace transform is an ambiguous one. Laplace transform can mean both the transformed expression and the transformation, and when we speak of the island we use both the expression Laplace transform and transfer function as were they synonyms. Whether to keep the original text or change it as suggested in Figure 19*b* is however more a question of how to interpret the expressions than a question of using the “correct” or “best” expression. If Laplace transform and Invers transform are interpreted as the transformed expressions, then already the original is valid, but since the actions are labelled the same - Laplace transform and Invers transform- the latter maybe to prefer. If the latter is preferred then the citation of the figure becomes problematic – which one is the correct? I have chosen to keep the model as we have used it in most of our journal papers, both because it is convenient, and because the expressions chosen made us actually notice that all islands were nouns and all arrows were actions, which was not possible to notice before the change of the name of the time function island (and keeping the name Laplace transform for the Transfer function)

8.2.3 Comparing the measured graph to the calculated graph – a triangular route – measured graph, time function and calculated graph

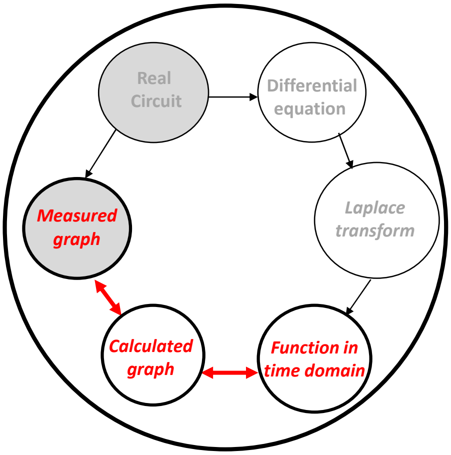


Figure 20: Comparing the measured graph and the calculated graph, a triangular route from function in time domain to the calculated graph, and between the measured and calculated graphs, where both links need to be in focal awareness simultaneously

The route from the function in the domain to the calculated graph, to the measured graph, is the main purpose of the lab "Transient response". The students are asked to compare a measured graph to a calculated graph, which in the computer program DataStudio, is called make a *curve fit*. The computer interface measures the voltages and currents chosen, here the input voltage, the output voltage and the current through the circuit. The time function can principally be one of two different functions: a damped sine wave or a sum of two exponential functions. Only one of the functions (the damped sine wave) is given in the lab, and the students are asked to start with that one, but are also told that they may need another function.

The lab-instruction states:

"Departing from the curve fits you have achieved, you will calculate the values of *R, L* and *C* these correspond to (requires that you derive the expression for the current with e.g. Laplace). Note that depending on the value of *R*, the suitable function to fit to will be different."[28]

The students are explicitly asked to keep two objects in focal awareness, and the two are from different worlds, but it is also necessary to have the third object, the function in the time domain in focal awareness simultaneously. Still in Figure 20 this is not a whole route, the triangular route expected by the title of this chapter. Anticipating next chapter, this is the indication that there is a need for one more link – a link between the measured graph and the time function. Such a link is however, not possible – there is no activity that can go directly from the measured graph directly to the time-function. We will return to this question in next section.

---

[28] " Utifrån de anpassningar ni får skall ni beräkna vilka värden på R, L och C detta motsvarar (kräver att ni löser uttrycket för strömmen med t ex Laplace). Observera att beroende på vilket värde som R har så kommer lämplig funktion att anpassa till att vara olika"

Although the Laplace transform, and its inverse transform, have been derived during the lectures (both courses) and in classroom-sessions (in the old course), only two groups start doing calculations in order to see what types of functions they may come up with, before they try to make a curve fit.

Only one group 2002 spontaneously starts calculating, group 22. They work very systematically already from start; go through the 4 measurements to do, makes the two first curve fits without any problems, and when they come to the third they notice that they need to find out which function to fit to and then start calculating(tape 2002_Group22_Tape_3 0:00). After around 30 minutes they have a result, which they test, i. e. they try the resultant function and values in their “user defined fit”. The curves do not match, and after testing 15 minutes Jock says:

```
2002_Group_22 _Tape_4 6:06

Jock: Well, shouldn’t the Laplace fit to
      what one has got, they ought to
```

He refers to what he has measured, and points at the screen when discussing with a peer group. The peer says, “so you got something that doesn’t fit too”. Other students come and go, disappointed that even this group, who have done the calculations can’t get it right; implicitly – so how would they?

The students are not used to having to do calculations in the lab room, but the teacher claims that it is necessary for them to do the calculations, and that they have enough time to do them. Still most students hesitate, and do not even look in their notes from problem-solving sessions or lectures spontaneously (some don’t even bring their materials to the lab sessions at all).

One group, group 13, show their frustration:

```
2002_Group_13 _Tape_2 1:55

Jack: What fit I don’t have no fit I
      have nothing on this screen (.) user
      defined, user defined ... and just test.
```

The students try to find the teacher, who comes and helps the students to read the instructions. After a rather long conversation (starting at tape2_5:15) the student says:

```
2002_Group_13 _Tape_2 8:06

Jack: And we were supposed to understand
      this? (A and B giggle)
John: No, now it is about understanding. Now
      you have got a function and then it is
```

```
      to (.) well it is measured values that
      you should try to fi’ or model
      mathematically and try to recognize what
      type of function it may be
Jack: Well, I would not have guessed that
      one                                   points at the damped
                                            sine
John: No now you are at another one (.)
      cause the damped is more obvious
      on the first measured(.) with the
      coil (.) then it is also for the
      others then it is to figure out which
      type of function it may be. It is
      possible to figure out by looking at
      the (.) Laplacetransform of (.) of
      the current
Jack: mm
John: how the poles are located
Jack: Now this was all too advanced
John: mm
Jack: We (.) never manage on our own
George: Yea                                         (giggling)
Jack: So, it is just to Laplacetransform
      and find the poles then
```

This last utterance from the student, repeating the exact wording of the teacher, comes not only here (at Tape2 8:23), but is repeated several times during the lab:

```
2002_Group_13 _Tape_2 13:03

Jack: We are supposed to do some tiny
      adjustments and make them fit, and
      doing that you use the Laplacetransform
      and find the poles
```

and

```
2002_Group_13 _Tape_2 14:40

Jack: Run the Laplacetransform and find the poles
```

and again about 45 minutes later when he finally has started to do the calculations he does not want to answer his fellow student’s question but tells how he is occupied:

```
2002_Group_13 _Tape_3 15:50

Jack: I am doing the poles here
```

This repeated citation, shows that the student has understood that it may be necessary to do calculations in order to know what to do, still he and his group do not start doing the calculations until about an hour later, and when doing calculations he doesn't want to be disturbed, until he has reached the result.

While he is doing the calculations his fellow student is trying to start with the first curve again, where the function was given (the damped sinewave). They had worked on that curve for about 25 minutes and were rather satisfied, but noted that they couldn't see the "curve pass zero". Jack notices that he needs to find out what the parameters in the function may correspond to. He asks the other teacher, who helps him to discuss the frequency, parameter *c*, and the damping, parameter b, and when they have found that the damping parameter defines the declining amplitude of the sinewave, the student manages to do the curve fit. After the discussion with the teacher it does not take more than 4 minutes to complete the first task, and 10 minutes later he has already finished the second measurement and curve fit.

All groups 2002 except Jock's, need help with as well the first curve fit as the third. Although they get the function in the first one, they do not know how to start choosing parameters. They have difficulties predicting how the graph will change with the change in parameters. Often in mathematics courses the drawing of graphs has been to draw a simple function, e.g. a sine wave or an exponential function, but combined is seen as "just to apply". The teachers here show the students how to think of the parameters one at a time, parameter *c* is the frequency of the sine wave and *b* is the damping. Using a too large value of parameter *b* makes the damping so quick that the "sine wave has not yet started to oscillate" (Teacher 2 tape 2002_g13_tape 2 31:46). When the students do the second curve fit, they know how to do, since it is the same procedure again; no one asks about the second curve fit.

However when they come to the third measurement they need to change the function to fit the measured graph to. All students except Jock's group try the damped sine again although they notice that it cannot be. When teacher1 comes to Anne and Beth he asks

```
2002_Group_11_Tape_3 17:34

John:  Is it obvious that, how does, it obvious
       that it is a damped sine
Anne: No but we didn't have any other guess
John: What others could you choose from?
Anne: Don't know
John: Well it doesn't have to be a trigonometrical
Anne: an x²?
John                                       (giggles)
Anne: What is your guess?
John: I don't guess
```

Here Anne and Beth have at least three times before doubted that it could be a damped sine, but still continued with that one, since they didn't know any better function to choose from. They get help and together with the teacher and students from another group they start using a sum of two exponential functions. One of the parameters *a* or *c* should be negative, and when the students after about 6 minutes try a negative value for parameter c, their reasoning changes to a more systematic change of parameters, and within a couple of minutes they are satisfied with their results.

The link between the measured graph and the calculated graph is not possible to make until the link between the time function and the calculated graph is made. On the other hand the link between the time function and the calculated graph has to be made in both directions – it is not sufficient to have drawn curves from functions in a math class, it is also necessary to be able to analyze what function a graph represents, to go from graph to formula.

Thus to make the link from measured graph to calculated graph requires to have both graphs and the time function in awareness at the same time, still there seems to be no direct link between the measured graph and the time function, which the title of this section (triangular route) suggested. Possibly this link is emerging, but as far as the videorecordings show, the link between the measured graph and the time function always goes through the calculated graph. Those students who refuse to accept that calculations are necessary never show the link between the mathematical expressions, the formulae and the graphs. All students who finish their measurements before they take on the mathematical work, ask after each curve fit: “Is this good enough for the report?” One group actually leaves the lab room in frustration:

```
2002_Group_24_Tape_5 2:07

A:     You’ll get a brain tumour from this. I’ll
       f-n be farmer instead.
```

Also in 2003 there are groups who hesitate doing the math, even when there are explicit tasks to calculate, and one group sits for as long as two hours trying other types of functions, e.g. $ae^{bx} * \ln cx$ before they finally accept that they need to do the calculations. Since they in 2003 are forced to do calculations – there are explicit tasks – all students do calculations and after they have done so, the question “is this good enough for the report” never occurs in 2003. Without the mathematics the gap was a *lingering gap*, whereas with mathematics *the gap was filled*.

8.2.4 The links across the circle – from transfer function to calculated graph and from measured graph to transfer function

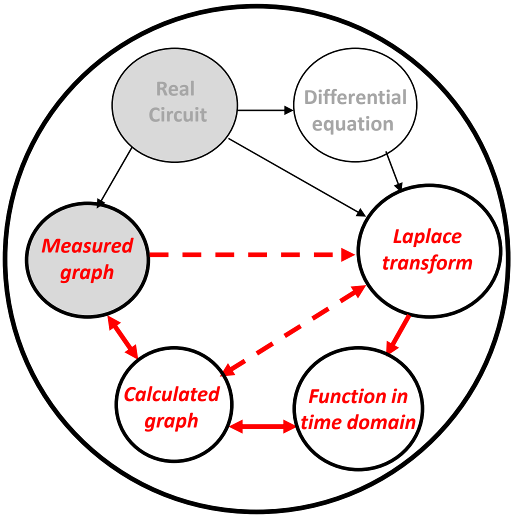


Figure 21: The links across the circle – from the Laplace transform, transfer function, to the calculated graph and from the measured graph to the Laplace transform

The links across the circle, from the transfer function or the Laplace transform to the calculated graph and the link from the measured graph to the Laplace transform were not found in 2002. While studying the video recordings from 2002 the researchers suggested that a link between the transfer function and the calculated graph should be introduced. The reason was that following the circumference of the circle would make it possible to transcend the two worlds (theory/model and object/event worlds) only by two links, and if it were possible to transcend the worlds on more occasions it would facilitate for the students to go between the worlds more freely. Simulations would make the link from the Laplace transform to the calculated graph possible for students, but also give students a repertoire to interpret the measured graph in terms of possible transfer functions (the two dashed arrows in Figure 21). Now the triangular route – measured graph, Laplace transform, calculated graph – would be possible, but also to make a whole from all four objects marked in the figure above. (Note that there is no possible activity directly between the function in the time domain and the measured graph, and that the arrow between the measured graph and the Laplace transform is a one-way route)

Thus simulations were introduced in the new course. Students were asked to use Simulink (Matlab™) to show the graphs in the time domain using six different but similar transfer functions, the same that they also in the new course were asked to calculate the inverse transform to. The examples were chosen so that only one parameter was altered at a time, but so that all three different kinds of poles were rendered (two real, two identical real or two complex conjugated roots to the characteristic polynomial) and two different relationships between the numerator and denominator polynomial were explored:

$$G(s)=\frac{2s+5}{s^2+2s+5} \qquad G(s)=\frac{2s+5}{s^2+2s+1} \qquad G(s)=\frac{2s+5}{s^2+2s+0.75}$$

$$G(s)=\frac{3}{s^2+2s+5} \qquad G(s)=\frac{3}{s^2+2s+1} \qquad G(s)=\frac{3}{s^2+2s+0.75}$$ [29]

Some students start doing simulations and some start with the mathematics. In both groups video recorded, one person starts with the simulations and one with the mathematics.
In 2003 the labs are integrated with the problem solving sessions, so two four-hour sessions are video recorded. The first session most of the problems from 2002 can be noticed, also the hesitation to do "the maths". One group (the group sitting next to 2003_G1, and thus seen on G1's video tapes) works together with Benny (male student in 2003_ G1) and although they have done the simulations they try to make curve fits without doing the calculations. The first two curve fits are rendered rather systematically, but when they start with the third, they do not know which function to fit to. They ask themselves several times whether to calculate or not, but still think it will be too much work, especially since Tess (the female student in group 2003_G1) has been doing calculations and still does not have any results. Interestingly they keep testing different functions, e.g. ae^{bx} * lncx for as long as two hours, not getting anywhere, just to avoid the tedious calculations. Finally Benny says:

```
2003_Group_1_Tape_4 13:02
Benny: Can't you calculate what it should be
C: of course you can
Benny: That has to be the most convenient way to find out
T1: You could at least calculate what type of function it may be
```

Now also these students start doing calculations, and after finishing the first calculation, they know exactly what to do, so when they come back two days later, they have done the rest of the calculations as homework, not only the calculations from the tasks mentioned above, but also the ones with the values of R, L and C from the lab.

The student who starts with the calculations, also starts with great hesitation, but as soon as her group have the results from the simulations she goes to another group, where they have also done the simulations and now started to do calculations. They start to work together, and although it takes them almost the rest of the first session, they still keep on doing the tasks. For this group as well for the other group, the way of working with the curve fits is much more systematical already from start and no one this year asks "Is this curve good enough for the report?" They know what to expect, and that they have "got it right".

The simulations helped the students to know what kind of answers to expect from the tedious calculations, and although they hesitated to do the maths, they kept working until they got the

---

[29] The last one has changed during this research work. By mistake the suggestion in the lab-instruction was 0.25, which would render nasty results, so already 2003 during sessions it was changed to 0.51 or 0.75, thus some of our papers demonstrate the last example with the two alternatives. Either of the three will render damped sinusoidal functions.

results. In terms of threshold concepts this would be to be in *the liminal space*, that is necessary for passing the threshold to enter through the portal. The simulations constituted *the key* that opened up the liminal space.

8.2.5 The link from circuit to measured graph

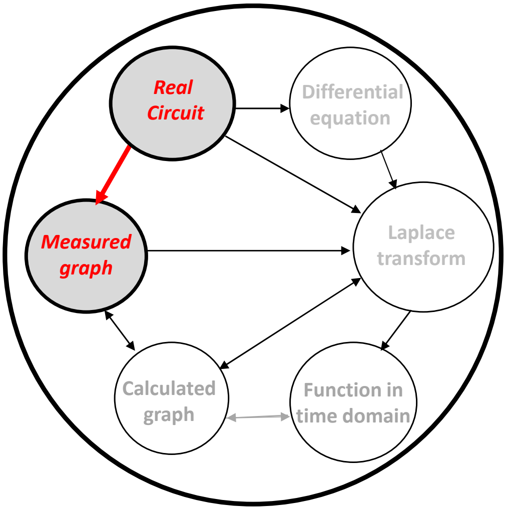


Figure 22: The link from the real circuit to the measured graph

The link from the circuit to the measured graph is about doing the measurements, i.e. how to connect the circuit, and to choose what to measure, and the other direction from graph to circuit is to analyze the measured graph in terms of what it physically means.

Two different questions occur, one is “What does ‘connect over the whole circuit’ mean?” and “What is the step response?”. The first one concerns confusing semantics. The output voltage from the computer interface is the input voltage to the circuit and the output voltage from the circuit is measured by a “voltage sensor”. The teacher shows how to do it and the problem is solved.

The other one is a matter of how to retrieve a step response. In theory classes a step is easily taken for granted as a theoretical construct, but in labs the easiest way to generate a step is to use a repeated step, which means that a square wave of low frequency is used. One group actually uses a square wave with too high frequency and asks why the step does not reach zero, a matter that the teacher does not notice. Later the group uses an appropriate frequency, and gets the step right.

As soon as the students recognize the rising edge of the square wave as a step this issue is resolved.

8.2.6 Reflections to follow up in the discussion

To make links is not just to apply the mathematics, but to use mathematics and measurements to create the relationships that are necessary for learning. In terms of *Practical Epistemologies* (Wickman, 2004), to *make links* is to *fill gaps*, the learning is in the students actions. It was not possible to see the links until we used this method to analyze what students did. From Variation theory we had learned that keeping more than one concept in *focal awareness simultaneously* (Marton & Booth, 1997) was a condition for learning, but to have two concepts in focal awareness is not just to learn a relationship, it is to carry out an action that gives meaning to both concepts, to make a link. As well Marton and Booth (1997) as Molander (1993) speak of learning as *becoming aware* of something not earlier noted, what Wickman (2004) calls *notice gaps.* They also talk about learning as *seeing things in a new way,* but in order to do so it is necessary to *fill the gaps*, which in our model is to *make links*. Phenomenology highlights the intentionality – how certain aspects are brought into focal awareness, and the whole/part-relationship shifts in focus, and pragmatists highlight the activity, the learning, the becoming aware, that makes it possible to proceed with a task. The knowledge is in action but also the learning is action.

To facilitate learning is not just to teach each island, each concept, but also to make the students *do* what is needed in order to *make links.* As noted above, when a gap is noticed, students enter what in terms of *Threshold concepts* is called *the liminal space*. As noted by the founders of threshold concepts this liminality is required, when learning threshold concepts. We have however noticed that it is possible to help students as well enter into, as pass the liminal space through highlighting *critical aspects* of the links as well as the two (or more) islands that need to be kept in focal awareness simultaneously. One example is the combination of calculations and simulations, where very systematically varied examples, varying the critical aspect that is to be focused (here the different kinds of graphs that are possible), makes the students as well enter the liminal space but also gives them an opportunity to see the way out. To find these critical aspects is to find the keys to learning, which I have called *key concepts*. In this lab the key concept is the palette of possible solutions.

8.3 Task Structure – Analysis of the lab instructions before and after changes

8.3.1 Ideas about what to change

The most obvious problem in the first course was that the students did not recognize the graphs as showing either a damped sine-wave or a function of two added exponential functions. It seemed very important to highlight this. This was already mathematically dealt with in lectures and problem-solving sessions, and the text book suggests systematically varied mathematical examples, but no graphs are asked for. In the lab when the students are asked to link the graph to a function in the time domain, the two functions are not in their focal awareness, seemingly to them just any mathematical function (as well x2 as ln x functions are guessed upon) would be possible. To notice that the functions have to be solutions to differential equations, and thus exponential and that second order systems always give either the damped sinewave or two added exponential functions, are *critical aspects* from the theory/model world that needs to be linked to the experimental graph in the object/event world. However there is no direct link between the function in the time domain and the experimental graph; the link has to go via the calculated graphs.

Thus it is necessary for the teachers (and researchers) to notice that the calculated and measured graphs are not the same for students, and that they actually belong to different worlds – the mathematically derived graph in the theory/model world and the measured graph in the object/event world.

Therefore one of the changes in the lab-instruction was to make the students draw graphs from the solutions to the differential equations, solutions they received through inverse Laplace transformation of examples that could represent transfer functions of the kind they would be able to measure in the lab. One way of doing this was to make the students work on the inverse Laplace transforms in mathematical terms, by hand, and another to let them elaborate the graphs through Matlab Simulink, where transfer functions are evaluated numerically, and graphs achieved directly. By using systematically chosen transfer functions that would show the two significantly different curve types, with reference to the two different kinds of poles to the denominator polynomial, as well as some other critical features such as the limit value, it was argued that it would become easier for the students to identify the curves they measured, i.e. find out what mathematical function would correspond to the measured graph. It was also argued that not until the students had begun to do some mathematical work on the Laplace transforms would they possibly be able to fit the measured curve to the user defined function. The normal text books would offer transfer functions with randomly chosen constants, and many of the resulting time-domain-functions that are calculated would never occur in the real world.

The changes in the instructions were thus to

1) Include a part where the students elaborated the six transfer functions in Matlab, Simulink, drawing conclusions about how the graphs were related to the transfer functions

2) Make the students do the calculations intertwined with measurements.

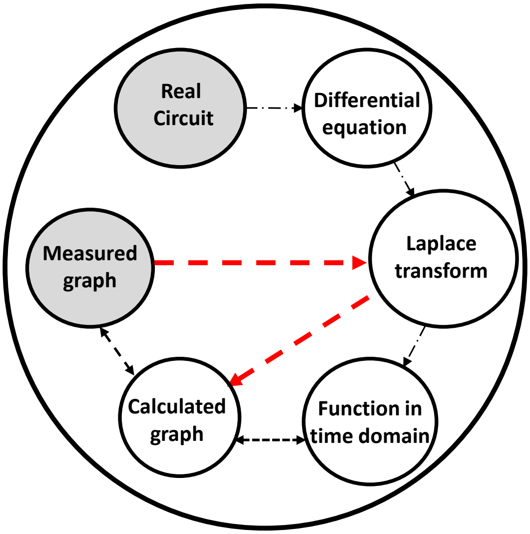


Figure 23: Modelling possible new links between the theory/model world and the object/event world, through introduction of simulation and calculation of systematically varied examples of transfer functions.

By the introduction of simulations the arrow from the Laplacetransform, the transfer function in the s-domain, to the calculated (simulated) graph would be a possible link for students to make. This link was not seen in any of the groups 2002, except the group who made calculations. Also the link between the measured graph and the Laplacetransform is now possible to make, i.e. to compare the transfer functions to the measured graphs. This link is a new link between the two worlds (object/event world and theory/model world), which we anticipated to have great impact on the students understanding since it transcends the two worlds, thus being a critical aspect in terms of the theory of variation. To compare the measured and the simulated curves, and at the same time compare the simulated graphs to the Laplace transforms they were derived from, would make it possible also to go in the direction from the graph to the transfer function, thus making the arrows making up whole routes, and not just fragmentary *dead-ends*.

The problem with the step response was not considered to remain as a problem after the simulations in Simulink, since the input block would have the name STEP, and the step response would be discussed during that new part of the lab.

Since we have found that students seldom want to, what they call, “waste time” by doing calculations during the lab sessions, even when they are asked to, we inserted the calculations at a point in the lab-instruction where the students would try the most difficult example during the lab session (and also get some hints from the white board on how to do it) and then be asked to do the rest of the examples at home, between the two sessions. By this we would possibly gain as well that the students would study more continuously during the course as would they bring materials from lectures and home work to the lab room.

8.3.2 Analysis of the tasks after changes

(This chapter is copied from our paper Carstensen & Bernhard 2009 p. 398-401)

For students to learn a specific object of learning they must become focally aware of its critical features, i.e. students have to discern these features. Such features, along with the pattern of variation in the task structure, constitute the enacted object of learning, i.e. what is possible for the students to learn. Therefore, we provide a quite detailed analysis of the task structure in terms of what is varied and what remains invariant in the different tasks. A brief summary of the task structure in the new and old versions of the lab is presented in Table 5. The first four tasks in the new structure were not part of the original design but, as discussed below, inclusion of these new tasks has proved to be essential for students' learning.

Brief description of task		**New course**	**Old course**
Scheduled time	Lecture Class (problem-solving) Problem-solving lab/Lab	4 h - 2 × 4 h	4 h 6 h 4 h
1a.	Simulate the step response for six systematically varied transfer functions	•	-
1b.	Obtain "by hand" the mathematical function in the time-domain for the six-step responses in task 1a.	•	-
2.	Obtain the expression for the transfer function of an *RLC*-circuit with *R*= 100 Ω, *L*= 100 mH and *C*= 100 µF.	•	-
3.	Calculate the step response $y(t)$ for some values of *R*, *L* and *C* that correspond to the values of the real circuit (used in coming tasks).	•	-
4a.	Measure the step responses $i(t)$ and $V_C(t)$ for a real *RLC*-circuit. *R* is varied while *L* and *C* are kept constant.	•	•
4b.	Measure the step responses $i(t)$ and $V_C(t)$ for the *RLC*-circuit in task 4a. *L* is varied while *R* and *C* are kept constant.	•	•
4c.	Measure the step responses $i(t)$ and $V_C(t)$ for the *RLC*-circuit in task 4a. *C* is varied while *R* and *L* are kept constant.	•	•
5a.	Fit a mathematical function to the four different experimental curves for $i(t)$ obtained in task 4a.	•	•
5b.	Use the fits obtained in task 5a to calculate the values of *R*, *L* and *C*.	•	•

Table 5: An overview of the task structure and organisation in the transient response lab according to the new and old designs

Task 1a-b: Simulate and calculate the step response for six systematically varied transfer functions
In this first task (or, more strictly, set of several related tasks), students studied six systematically varied transfer-functions[30]:

$$G(s)=\frac{2s+5}{s^2+2s+5} \qquad G(s)=\frac{2s+5}{s^2+2s+1} \qquad G(s)=\frac{2s+5}{s^2+2s+0.51}$$

$$G(s)=\frac{3}{s^2+2s+5} \qquad G(s)=\frac{3}{s^2+2s+1} \qquad G(s)=\frac{3}{s^2+2s+0.51}$$

Two separate dimensions of variation were used in this task. One was variation in the s^0-term a_0 of the denominator polynomial, while a_1, a_2, and the numerator remained invariant, and the other was in the s^1-term b_1 of the numerator polynomial, while b_0 and the denominator remained invariant. Varying a_0 in the denominator of $G(s)$ results in different types of poles, as shown in Table 6:

$\boldsymbol{a_2}$	$\boldsymbol{a_1}$	$\boldsymbol{a_0}$	Roots of $\boldsymbol{a_2s^2+a_1s+a_0}$ (poles)	
1	2	5	$-1+\sqrt{1-5}=-1+2j$	$-1-\sqrt{1-5}=-1-2j$
1	2	1	-1	-1
1	2	0.51	$-1+\sqrt{1-0.51}=-0.3$	$-1-\sqrt{1-0.51}=-1.7$

Table 6: Roots of the different denominator polynomials of Ga(s) – Gf(s).

Initially, the students were asked to calculate the step response function in the time domain for the transfer function G_a "by hand", thereby obtaining the inverse transform of $1/s\cdot G(s)$. They were also instructed to use MATLAB® and Simulink® to simulate the step response of G_a. The students were then instructed to do the same for the transfer functions $G_b(s)$-$G_f(s)$, before comparing the resultant time-domain step responses in an attempt to relate the observed changes in the graphs to changes in the coefficients. In particular, the students were asked to notice the final values of the obtained curves and their initial behaviour, while trying to relate them to the transfer function's parameters.

The step responses for the six different $G(s)$ are compiled together in graphical form in Figure 24, where several important characteristics can be observed:

1) The different types of solutions (complex conjugate, double or two distinct real roots) of the denominator polynomial (the poles of the transfer function), result in three qualitatively different ways of approaching the steady-state,

---

[30] The term a_0 in the 3rd denominator-polynomial has been altered. 2003 it was accidently set to 0.25, which rendered extra nasty calculations, so the teacher suggested the use of 0.75 or 0.51 instead. These two have alternatively been used in our presentations and papers.

2) The steady-state value of the step response can be seen to depend on the transfer function's limit-value when s approaches zero, i.e. the ratio b_0/a_0.

3) It is apparent that the initial behaviour of the response function depends on the numerator polynomial, and not on the variation of a_0 in the denominator polynomial.

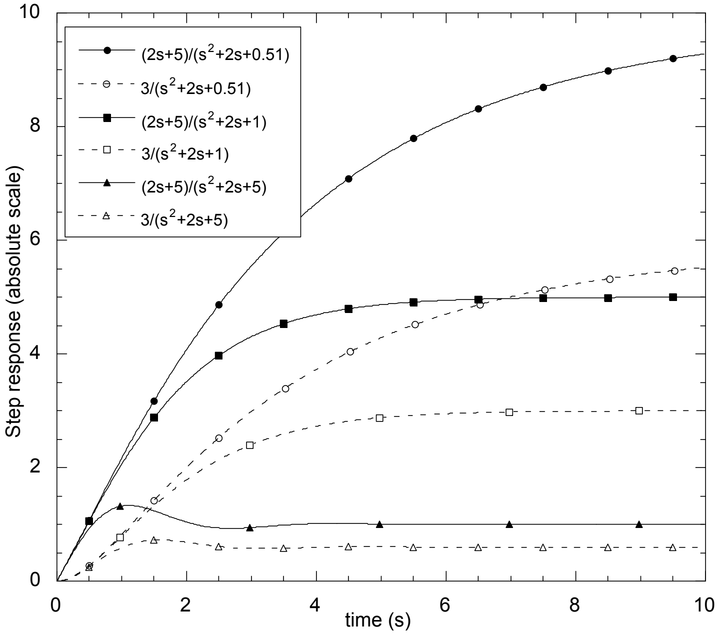


Figure 24: Step responses for transfer functions with different denominators, a) with 2s+5 in the numerator [Ga(s)–Gc(s)], and b) with 3 in the numerator [Gd(s)–Gf(s)].

Instructing the students to obtain the response through simulations and "hand" calculations 'opened-up' for awareness of the connections between the mathematical parameters of the transfer function and the resultant step response. Furthermore, the values of the numerical coefficients a_0, a_1, and a_2 were chosen to allow simple "hand" calculations, ensuring that the physical meaning of the obtained parameters and functions, and not the mathematical manipulation, were in the students' focal awareness.

Tasks 2-3

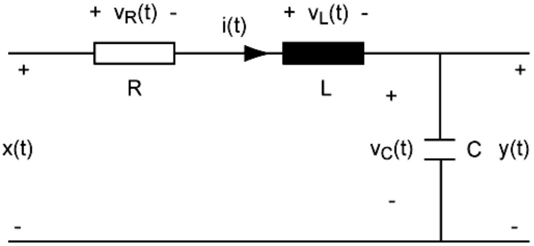


Figure 25: The system, an RLC-circuit, studied in the transient response lab.

The students' next task was to derive $G(s)=Y(s)/X(s)$ for the circuit in Figure 25, where $R=$ 100 Ω, $L=$ 100 mH, and $C=$ 100 µF. Students were then asked, based on physical as well as mathematical reasoning, how (and why) $y(t)$ would be affected if C was changed from 100 µF to 10 µF. This assignment was built upon in task 3, in which students were asked to calculate the response $y(t)$ for different values of R, L, and C used in the lab when $x(t)$ was a step, i.e. $x(t) = 0$ V, $t < 0$; 1 V, $t \geq 0$. Students were then asked to identify *the* coefficients in the time function in relation to R, L, and C, with a hint that a comparison with task 1 would be helpful. In essence, these tasks involved the derivation of $G_{\mathrm{Vc}}(s)$ and $V_C(s)$, and the calculation of $v_C(t)$ through the inverse transformation of $V_C(s)$.

Task 4

This was the first experimental task in the new lab design and the first actual task in the old version of the lab. The current $i(t)$ through and the voltage $v_C(t)$ over the capacitor in an *RLC*-circuit was measured by sensors connected to a computer-based system, which collected, processed and visually presented the experimental data. The voltage step $v_{\mathrm{in}}(t)$ was generated by using a low-frequency positive square wave. In the first experimental task, R_{res} was varied while L and C were kept invariant.

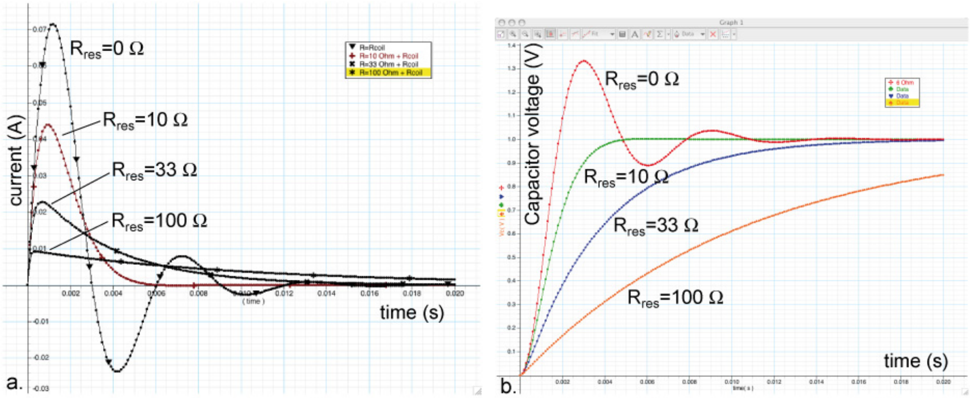


Figure 26: Experimental curves for the current (a) and the capacitor voltage (b) for different values of Rres (L=8.2 mH and C=100 µF).(Carstensen & Bernhard, 2009, p. 404)

The qualitatively different ways steady-state was approached are shown in Figure 26, which in this case depended on the value of the resistance R (with L and C constant). The different responses for $i(t)$ and $v_C(t)$, due to differences in the order of the numerator polynomial in their respective transforms (cf. Table 9) are also shown in Figure 24.The values of R_{res}, L, and C used in the task are presented in,Table 7, together with the resultant mathematical expression of the current $i(t)$ (obtaining the latter was part of task 5). In addition, the total resistance was higher than the nominal resistor value R_{res} since the coil resistance R_{coil} was ≈ 6Ω.

R_{res} (Ω)	R_{tot} (Ω)	L (mH)	C (μF)	Roots of $s^2 + \frac{R_{tot}}{L}s + \frac{1}{LC}$		$i(t)$ (A)
0	6	8.2	100	$-366 + 1042j$	$-366 - 1042j$	$0.1170e^{-366t}\sin(1042t)$
10	16	8.2	100	$-976 + 517j$	$-976 - 517j$	$0.2357e^{-976t}\sin(517t)$
33	39	8.2	100	-272	-4484	$0.0290(e^{-272t} - e^{-4484t})$
100	106	8.2	100	-95	-12832	$0.0096(e^{-95t} - e^{-12832t})$

Table 7: Variations in terms of Rres, with L, C, and E constant. Note that the frequency, ω_d, of the damped system changes with R and is not equal to ω_n.

The second sub-task (task 4b) involved obtaining experimental curves when *L* was varied (while *R* and *C* were kept constant), and the third sub-task (task 4c) involved varying *C* (while *R* and *L* were kept constant). The values for the variations used in task 4c, along with the results in mathematical form, are presented in Table 8:

R_{res} (Ω)	R_{tot} (Ω)	L (mH)	C (μF)	Roots of $s^2 + \frac{R_{tot}}{L}s + \frac{1}{LC}$		$i(t)$ (A)
0	6	8.2	100	$-366 + 1042j$	$-366 - 1042j$	$0.1170e^{-366t}\sin(1042t)$
0	6	8.2	330	$-366 + 485j$	$-366 - 485j$	$0.2514e^{-366t}\sin(485t)$
10	16	8.2	100	$-976 + 517j$	$-976 - 517j$	$0.2357e^{-976t}\sin(517t)$
10	16	8.2	330	-213	-1739	$0.0799(e^{-213t} - e^{-1739t})$

Table 8: Variations in terms of C, where Rres= 0 and 10 Ω, while L and E are constant.

Task 5

In the final task students were asked to fit mathematical functions to each of the four measured curves for *i*(*t*), using tools for manual user-defined fitting incorporated in provided software. As shown in Figure 26a, there are two qualitatively different responses, type $i(t) = ae^{bt}\sin(ct+d)$ and $i(t) = ae^{bt} + ce^{dt}$, and only the former type was provided in the lab-instructions. The software also allowed the students to display both the measured and calculated graphs in the same diagram. Hence, the students had to decide the type of function to fit to as well as appropriate values for the constants. They were also required to calculate the corresponding *R*, *L*, and *C* values from their fitted curves. To do this, a fit to measured data in the form,

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

or

$$i(t) = ae^{-bt} + ce^{-dt} => I(s) = \frac{a}{s-b} + \frac{c}{s-d}$$

could be compared to the form for *I*(*s*) (see Table 9) for calculating *R*, *L*, and *C*. Alternatively, the nominal values for *R*, *L*, and *C* could be used to calculate a first approximation of *i*(*t*).

In addition, the nominal and fitted values of *R* disagreed due to the resistance of the coil, while the nominal and fitted values of *L* and *C* were usually in good agreement. The qualitatively different functions obtained for *i*(*t*) can be found in Table 7

Current	**Capacitor voltage**
Transfer function	
$G_I(s) = \frac{I(s)}{U_{in}(s)} = \frac{\frac{1}{L}s}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$	$G_U(s) = \frac{U_C(s)}{U_{in}(s)} = \frac{\frac{1}{LC}}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$
Derivation of G(s) and step responses in the s-domain	
$I(s) = U_{in}(s)G_I(s) = \frac{E}{s}\frac{\frac{1}{L}s}{s^2 + \frac{R}{L}s + \frac{1}{LC}} =$ $= E\frac{\frac{1}{L}}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$	$U_{out}(s) = U_{in}(s) \cdot G_U(s) =$ $= \frac{E}{s}\frac{\frac{1}{LC}}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$
Step response in the time domain	
$\begin{cases} i(t) = ae^{bt}\sin(ct+d) \\ i(t) = ate^{bt} \\ i(t) = ae^{bt} + ce^{dt} \end{cases} \begin{cases} \frac{1}{LC} > \left(\frac{R}{2L}\right)^2 \\ \frac{1}{LC} = \left(\frac{R}{2L}\right)^2 \\ \frac{1}{LC} < \left(\frac{R}{2L}\right)^2 \end{cases}$	$\begin{cases} u_{out}(t) = a(1 - e^{bt}\sin(ct+d)) \\ u_{out}(t) = a(1 - te^{bt}) \\ u_{out}(t) = a(1 - (e^{bt} - e^{dt})) \end{cases} \begin{cases} \frac{1}{LC} > \left(\frac{R}{2L}\right)^2 \\ \frac{1}{LC} = \left(\frac{R}{2L}\right)^2 \\ \frac{1}{LC} < \left(\frac{R}{2L}\right)^2 \end{cases}$
For examples of i(t) see Figure 26a	For examples of $v_C(t)$ see Figure 26b

Table 9: Summary of step responses and transfer functions for the current and the capacitor voltage. (cf. chapter 2.3)

8.4 New Discourse

As already briefly discussed in 8.2.4 the students work differently in the new course. Although we only video-recorded two groups 2003 we claim that there is a clear difference between the years and that the difference is due to the changes in the instructions. In the beginning of the lab the same questions are raised as in the old course, but since this is the last in a series of labs, where the students during the whole new course have worked with problem-solving and labs integrated, one student from almost every group start with the calculations. In this lab the variation of the mathematical tasks is very systematic, and some students ask whether it is necessary to do all of them, since they appear to be very similar, but in discussion with the teacher they conclude that it is better to do six systematically varied than to do the nine in the book which are not easily comparable.

The most obvious difference is the difference in the way students talk. In the new course there is very little discussion about process, and the discussions on the content are often very long continuous discussions.

This chapter consists of two parts, first a review of one group's path through the lab, and after that reflections on the differences in the groups' actions.

Group one consists of the students Tess and Benny, but since Tess is doing the calculations, Benny turns to the group next to him for questions on process and discussion of obtained results, thus actually three groups can be commented on although only two were recorded.

8.4.1 Group one 2003

The students start with the simulations in Matlab. Tess almost immediately starts with the calculations, while Benny tries to figure out what transfer functions they are supposed to simulate. Benny takes some help from the group sitting next to them. After about 10 minutes he has set up the transfer function for the *RCL*-circuit, calculates the different constants (depending on the possible combinations of *R, L* and *C*) to use in the transfer function. He starts with *R*=100Ω *L*=100mH and *C*=10μF and then they change to *C*=1μF and turns to the group sitting next to him:

```
2003_Group_1 _Tape_1 25:18
Chris: Yeah, and we should explain this mathematically and physically
Benny: Bu', how easy is this to explain
Chris: I think it ought to be the other way around, almost
Benny: Difficult to tell
Chris: Smaller capacitor, makes less resistance so it ought to go
       down faster
Benny: =Yeah
Chris: Less resistance so then the voltage will drop faster and
       since it is the voltage across the capacitor that we measure
Benny: =Yeah the voltage across the capacitor becomes faster,
       you may say
Chris: =Yeah it runs away faster
```

Benny: Yeah, here it is charging, and it does that faster when
it's small=
Chris: =Yes=
Benny: It's pretty obvious
Chris: Then it's the question why there is a peak=
Benny: Yes
Chris: It has to be some exchange between the capacitor and the
inductor there
Benny: The inductor gives a push here in some way, but the
inductor tries to counteract, not to forget, here 't is.
Chris: The inductor tries to hinder the charging of the capacitor
Benny: You can't say that the inductor sucks out the capacitor?
Chris: But now, wait a second, the capacitor is charged, the there
is current through the inductor, and then when it is full,
the capacitor , the current still continues to come,
since the inductor wants it to keep on for another while
Benny: =Yes=
Chris: Then it becomes even more charges in the capacitor than it
wants, so the voltage raises a little more=
Benny: =Yea since the inductor=
Chris: =Then it falls back since the capacitor throws that voltage
overcharge back out because it can't keep it.
Benny: Yeah, 'cause when the inductor has evened out 'cause the
current decreases

Already here in the beginning of the lab there are vivid discussions on subject matter.

They now go on with the examples from the appendix, but add:

2003_Group_1 _Tape_1 25:18
Benny: Alright, it's just to do as it says here then, but
have we've gotto calculate, What's the use
of calculating when the computer has already done it?
Chris: You can't sit here and calculate what it will look like
Tess: What?

(raises from her calculations)

Chris: Calculate the step response
Tess: Yes you can
Chris: We have a differential equation for how this circuit will
behave over time
Tess: Yes, but only when you have inverse-transformed it you
will get it back

The discussion goes on for a while where the guys consider it to cause too much work and Tess concludes "so you might as well get started!" Next Chris and his fellow student start to calculate the inverse transform, using Maple to do the partial fractions, and then do the rest by hand, but they do not finish. Benny fetches the lab-board and wires up the circuit and starts DataStudio (the program which shows the measured graphs) Tess continues to calculate the inverse transforms for the six examples. After about one hour of the lab session the teacher is asked to do one of the examples on the white board, which he does. (All students are not participating, only those doing calculations.) This takes about 20 minutes. After about two hours Benny has made some measurements and is trying to fit the damped sine-function to his graph. He turns to his neighbours:

```
2003_Group_1 _Tape_3 22:49
Benny: Do you know what we'll get from this?
Chris: Sort of
Benny: Well, here I am now                points to the screen
       To make it raise I have to
       increase
Chris: Think like this: This is a sine
       wave that rolls away, and here     points to the screen
       well (.) let's see (.) here is
       the amplitude
Benny: Ok, I can see that
Chris: The damping
Benny: Yeah
Chris: How fast it declines (.) Here it
       declines too little You have
       to damp it harder.
```

This discussion goes on for another minute or so, and after this Benny has no problems to finish this first curve fit. After half an hour both Benny and the neighbours have finished both of the two first measurements and have problems when fitting the third. They call for the teacher who asks if this is the right function, and the students answer that they don't know. The teacher asks what they think the curve looks like, but the students don't know. They start guessing, but do not suggest exponential functions even if the teacher tries to get them to. Thus the teacher asks them if they have done any calculations, which none of them have. Chris had started to calculate by means of Maple, but quit when he did not know what to expect. Tess who has been calculating the whole lab session now takes a calculator and gets a graph calculated from one of the exponential functions that she has received through the inverse transform, and shows the guys. The guys hopes for a simpler way to get the right curve than to have to do all the work Tess has done. They try different kinds of curves e.g. $a*e^{-bx}*lnx$. After a while Benny utters:

```
2003_Group_1 _Tape_4 13:02
Benny: Can't we just calculate what it should look like?
Chris: Of course we can
Benny: But that's gotta be the simplest way
```

They start to do some calculations but decide that they can as well do it at home before the next lab session.

A week later they are back for the second session. The session starts with a discussion:

2003_Group_1 _Tape_1_Session2 00:00
Tess: I think we are supposed to process this curve.
Benny: Add a curve?
Tess: Mm..
Benny: Yea, then we'll have to do that.
Tess: But do you think we should go back to the 10Ω:er first, and do
it on that first, and then measure each one again?
Benny: Yea, that's what we'll have to do. Connect the 10Ω:er.
I didn't save anything.
Tess: It doesn't matter.
Benny: We can as well erase the graphs and do them again.
Tess: Mm..
Benny: Oh, yea, and I thought it would be so simple
(Benny starts measuring, and Tess studies the instructions)
Tess: But what else have you processed?
Benny: Ehh (.)I did it on (.)
Tess: I mean this with "fit" and such (.)
Benny: I did it with this one. (Points at the instruction)
The first one I did with this (points at the instructions
again). This one(.) an' then next one (.)'twas much more
difficult to fit 'cause then you need another formula to fit
to,
an' it's not so easy to know which one to use.
(Looks through the instructions)
Benny: Here one has to take the one he used.
Tess: OK
Benny: I guess this is the one. Let's see (.)
(Enters the formula into the computer)
Tess: Which formula are you using?
Benny: OK, this is (.) (continues writing on the
keyboard)
Tess: Well, I don't want to interrupt, but
I don't think that's the right formula.
Benny: You never know.
(continues writing on the keyboard to see what happens,
about one minute later Tess tries to interrupt again)
Tess: See, This here, this is for the damped sine-wave (points at
the instructions), It looks like this
Benny: Yea.
Tess: And that's not our curve!
Benny: Nop, (looks at the computer) It's not! (starts suddenly
turning the pages in the
instructions)
I was perhaps (.) I thought it would
be this simple (.) Ehh
(2s)

Tess: We could (.) (starts turning pages again, reviewing the whole instruction)

Benny: But what can we (.) (scratches his head, looks alternately towards Tess and the computer, mumbles)

Benny: I don't know what to do.

Benny: Let's see (.) What kind can this be?

Tess: (Difficult to hear) z is not in here, so I don't believe this is it.

Benny: But later it works, when we do this, but (.) yea, then the inductor is also in here yea, so, that’s another story, then you get the "sinedamped story" again, yea,
But this isn't (.) but(.). But isn't this an exponential graph maybe?!

Tess: But look at this, it just looks as one of those upgoing ones from an inductor, (.) At the lecture he showed one like this.

Benny: Wait now, just a resistor and an inductor, hey? Or a resistor and a capacitor?

(Tess reads her lecture notes and Benny his Lab-instructions)

Tess: No, this was the step-response.

Benny: But, just a second,

Tess: (interrupts) but that's what we have!

Benny: But we have an inductor in this. (wonders)

Tess: But test this one, this is the transient for an inductor. Just this part.

Benny: But this is only for an inductor (.) Nop, it's not, is it?

Tess: And I think this is for the capacitor. Yes this is the one for a capacitor (paus) But try something with an exponential function.

Benny: Yea, but where does it say anything about the exexpexponential function ehh (.) a*exp *a (.)

Tess: No, no, Not like that

Benny: Is it plus some phase shift ehh, do you think we can just add (.) ab, ab plus c comma zero (.) well, it
(writes the formula onto the computer)

Tess: It doesn't seem to work

Benny: Nop (.) Oh well, (.) But (.)
(continues to write on the keyboard)

Benny: Well, it's no use in just keeping on guessing.

Tess: No, it isn't. But if we make the rest of the measurements, and try to figure out the mathematics later.

Benny: But the measurements are made very quickly, it's rather automatic. There will be no measurements that we will save. It seems useless to record them. I will lose them anyway. They are so easy to make.

Tess: Mmm

Benny: I think, I think it's ,that we'd as well go ahead with the math.

Benny: We'd better do it straight away, now when we can get some help.
(Both students look at their notes and instructions)
Benny: What's this?
(They are looking at one page in their notes for about one minute)
Benny: Which capacitor did we use? 100?
And the last one was the (.) 10?
Well, this has to be the fourth one that we've got here!
Tess: But this is a little confusing. I don't see where it ends.
(Looks at calculations made in here notes)
We are supposed to fit the measured current.
Benny: Yea, that's it. I knew that. I didn't think about it.
(Starts writing on the computer again)
Tess: But I don't know if we are supposed to do this for all of them.
I'll check that.
Benny: Yes I think it is, but only the current.
Tess: What do you mean. current?

The discussion continues for a long while. This long continuous discussions are never found in the old course. Here the students know what to expect, they have done the calculations, they know which curves are possible etc. They have made the necessary links.

8.4.2 Modelling the students actions

It is obvious from both years that students have difficulties connecting the mathematical representation to the measured graphs and the circuit they use. Especially this is seen in the first half of the lab. As an example Tess has been doing all the calculations, and Benny has worked on the simulations, and when they after about 40 minutes are supposed to wire up the circuit they read:

Tess: "Wire up the circuit" (reads from instruction)
(turns her head towards B)
It seems taken for granted what circuit he talks about
Benny: Yea, we'd better read this again

Even though Benny had worked with the circuit in order to find the equation to work on, he has now forgotten which circuit he was working with. It does not take very long before they know which circuit to work on, but the stop here is typical of the gap that has not been filled yet.

The gap may also be illustrated by modelling what they have been doing (Figure 27):

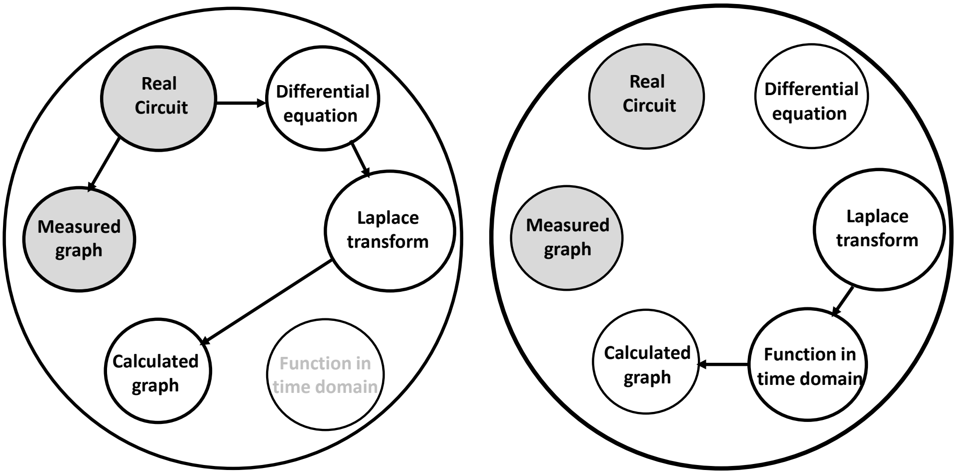


Figure 27: a) Benny's lived object of learning in this first part of the lab
b) Tess' lived object of learning in this first part of the lab

Tess and Benny have here encountered different objects of learning, and in order to fill the gap they have to make relations to what they know, what is standing fast. None of them is now thinking about the real circuit, because in order to do so they have to make links back, Benny from the graph and Tess from the mathematics.

That the students do not connect what is done in other previous sessions, especially lectures, is evident. For instance the comment that group three in the old course makes several times: “let's Laplace-transform an' check the pole-values” is a comment which shows that they have heard of the Laplace transform, but have no idea what it is. That this comment is constantly recurring is also a sign of a lingering gap. In the new course, where the lab sessions and problem solving sessions are integrated, the students are used to the fact that they need to bring their notes from lectures. In the old course this was only explicitly asked for in the problem solving sessions, and very seldom in the labs, although the teachers had expected the students to bring both books and notes to all sessions of the course.

To integrate the lab sessions and the problem solving session thus gives some important changes in the students' ways to handle the subject matter

1) They bring their knowledge from the mathematical context into the lab-room, but can also use the graphs when elaborating the mathematical context. And as a consequence they also bring their materials from the different sessions to all sessions.
2) When simultaneously working from as well the real world as the mathematical worlds, the students make the two meet, so that the gaps between the two worlds, may be filled

In the old course one of the questions asked, and asked several times by all groups, was: “Is this curve good enough for the report?” This question is never asked in the new course. The question seems to be stated because the students are not quite sure of what they have been doing, and have thus no idea of what to expect. It also shows that the students' expectations of the lab-work is most of all to pass the course. Of course the students were asked to do homework on problem solving (several examples were recommended in the course information) also in the old course, but they did not do that until late in the course.

Forcing the students to work continuously on the mathematical models during the course make them keep up with the course and thus learn more. The change is thus that:

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. to make links between all the components of the circle:

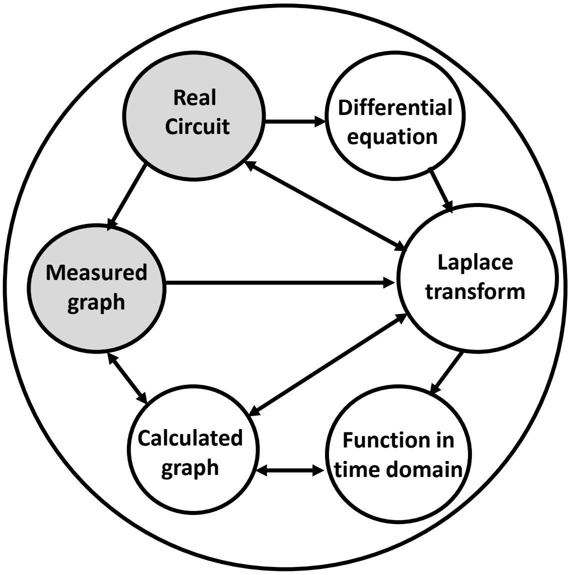


Figure 28: Links made at the end of the lab-work in the new course

At the end of the lab-session Tess and Benny have made all the links described in Figure 28.

9 Discussion

9.1 Validity of the model and thus this research

When working with qualitative research it is necessary to include a discussion on the validity. However equally apparent is the need for validation of a model. To evaluate data in different ways, by different methods, triangulation, is one way of doing this. Since the method in this work has been to make a model and used it as an analytical tool, validation in this work amounts to evaluate the validity of the model developed, used and analysed. The three first parts of the results chapter are retrieved in such a way that this validation is possible to make. The first project was to use students' questions and teachers' answers to obtain the model. The theory of practical epistemologies was used to model the concepts students discussed, the pathways they took when going from one to another, and what lingering gaps that was intended to fill. The second study, although the third part of the results chapter was to analyse the tasks in the lab according to the theory of variation. The third was to investigate the predictive power of the model – to analyze the change in discourse after changes in the instructions. The fourth was to reanalyse the data to investigate what the relationships between the concepts were, i.e. to learn more about the model, and how to use it, which led to the interesting finding that all relations were things to do, and not just relationships to learn.

In the validation process of a model often the model is refined. In this work the refinement was to make the names of the objects in the model clearer: both the name Inverse Transform and Laplace Transform are suggested to be changed. Both these terms can be used as well as nouns as verbs, i.e. the transformed expression and the transformation, which in the first study was not obvious. In chapter 8.2.2 this is discussed. It is not necessary to change the terms, but since the result of chapter 8.2 is that all *islands* in the model are nouns, and that all *arrows* are verbs, it was suggested that the terms *Inverse Transform* and *Laplace Transform* should be used as names on the arrows, and *Time Function* and *Transfer Function* as names of the islands. Since several journal papers already use the old terms it is not easily changed, but in future use of the model it is recommended to use nouns for the islands and verbs for the arrows. This is maybe not always possible since many of the verbs are also made into nouns as in the case of "transformation" sometimes without even changing the spelling, as in the case of "transform".

To use the model in analysis of the intended object of learning and then change the tasks so that the enacted object of learning becomes closer to the intended object, is also a test of validity. Hence if the results showing the lived object of learning is closer to the intended object of learning, after the changes, not only was the lab-task successful, but also the model.

When a model in engineering replicates the intended function of a future design this is regarded successful, and "If a model succeeds in producing the expected results or in replicating some features of the phenomenon it provides an interesting starting point for further model building." (Knuuttila, 2011, p. 268)

9.2 Linking the results gained from different theoretical backgrounds

The model of learning a complex concept, is a model that recognizes a complex concept as a concept that makes up a holistic system of “single” interrelated “concepts”. These may be connected by links representing something that students do. Our analysis of video-recordings from the lab-course in electric circuit theory show that all links have to be made by the students, they have to make links, create ways to pass from one island to another.

One of the links is to calculate the transfer function for a given circuit. This could be considered as “just something to learn”, but what does it mean to learn this? Molander (1993) gives a similar example: “mass is energy”, and claims about this and similar statements that “it is obvious that there is no *knowledge* in the *statements themselves*, there is something to know only if one *understands* the included *concepts* and the *activitycontext* where they belong.” (Molander, 1993 p., my translation, italics in original) The learning process is *in* the action.

To create links is to be aware of more than one *island* at the same time; to *make links* is to keep more than one *island* in *focal awareness* simultaneously. The model became a way to see what students had in focal awareness, while working with the tasks. But the model also became a way to see what students did not do, what concepts they worked with in isolation, i.e. what links they did not make. When they *made links* it was possible for the students to go on with the task, while when they did not make links, but focused on only one *single island*, at a time, the students were not able to go on with the task, and were thus hindered in as well the task itself as hindered in the learning process.

A necessary condition for learning is to keep more than one concept in *focal awareness simultaneously* (Marton & Booth, 1997), but to have two concepts in focal awareness is not just to learn a relationship, it is to carry out an action that gives meaning to both concepts, to *make a link*, a result which was possible to see when using *Practical Epistemologies* (Wickman, 2004). Although Marton takes his departure in phenomenology and Molander in pragmatism, they both speak of learning as *becoming aware* of something not earlier noted (Marton & Booth, 1997; Molander, 1993). Wickman calls this: *notice gaps* in order to *fill* them. Translating the term aware into Swedish renders two different meanings of the term: “erfara” and “uppmärksamma”. In English there are also synonyms: awareness and attentiveness (used as translation of the term “uppmärksamhet” in Wickman (2004, footnote p. 341). Going back and forth between the languages, comparing the synonyms, and also the philosophies underpinning the meaning of the words, the differences in the meanings do not so much become differences as they work as scaffolding tools when trying to understand learning. Both philosophies talk about knowledge as being aware, and learning as becoming aware of something in a new way. A slight difference in how to make research can however be noticed, and that is that practical epistemologies is looking at learning while it is going on, and phenomenography, the traditional research method in variation theory, asks the students what they have noticed afterwards. In learning studies (Runesson & Marton, 2002) also variation theory looks at authentic lessons or labs, which is a way to study learning while it is going on. The difference is that learning studies look at teaching sessions whereas practical epistemologies study students' own work. This means that learning studies study the enacted object of learning, and thus what is made possible to learn and practical epistemologies study the lived object of learning, and thus what students are learning. To combine the two methods is a way to study both the enacted and the lived object of learning. And by modelling the object of learning critical aspects come afore, so that also the intended object of learning may be modelled and analysed. The methods highlight different aspects of the object of learning, especially concerning the links between the two worlds, that would not have been possible to see with only one of them.

None of these methods could, however, explain why the students hesitated to do the maths – why would they not start doing the calculations required instead of just trying any known functions from mathematics classes? In the *threshold concepts theory*, this hesitation is called *liminality*. Threshold concepts are concepts which, when not learned, hinder the students to go on, and they tend to lead to mimicry until students enter the liminal state. In this study we could see that students randomly chose among different mathematical functions they could think of, instead of going ahead, "doing the maths".

To facilitate learning is not just to teach each island, each concept, but also to make the students *do* what is needed in order to *make links*. When students did not make links, i.e. when a "gap" is noticed in terms of *practical epistemologies*, students enter what in terms of *Threshold concepts* is called the *liminal space*. This liminality is required, when learning threshold concepts, but we have noticed that it is possible to help students as well enter into, as pass the liminal space through highlighting *critical aspects* of the links as well as the two (or more) islands that need to be kept in focal awareness simultaneously. Thus *the threshold concepts theory* helped us understand the hesitation, but *variation theory* offered an opening for student learning. One example is the combination of calculations and simulations, where very systematically varied examples, varying the critical aspect that is to be focused (here the different kinds of graphs that are possible), makes the students as well enter the liminal space but also gives them an opportunity to see the way out.To find these critical aspects is to find the *keys to learning*, which I have called *key concepts*. In this lab the *key* is the palette of possible solutions.

To do research is also a learning where making links is a necessary condition for learning. Our contribution to education research is that linking the theories of learning, phenomenology, pragmatism and threshold concepts is a key to understand learning.

9.3 Linking the theory/model world to the real world

When discussing the relationship between theory and practice, the focus has been on factual versus procedural knowledge. Tiberghien (2000) introduced another categorisation – the two worlds. The main reason for this is that she noticed that there is factual knowledge as well in the theory domain as it is in the practice domain, and there is procedural knowledge in both worlds as well. The word practice has two meanings – rehearse and to put something into practice e.g. in the medical practice, or to practice law. It is both a noun and a verb. In electrical engineering the factual knowledge in the object/event domain is e.g. data sheets. These do not describe theories about a component, but facts about the components' form, characteristics and performance. Reading them takes as well conceptual knowledge about data sheets, about what kind of data to expect, as procedural knowledge about how to read them and how to apply the data onto a circuit. In the theory/model world there is also both kinds of knowledge, conceptual knowledge of voltage, current and impedances, as well as procedural manipulation of mathematical expressions. Our research resonates well here with Tiberghien's work, especially when discussing students' difficulties or the intended links between the two worlds. It is the links between the worlds that are the more difficult ones to make, and it is between the worlds that linking theory to practice fails. Ryegård (2005) speaks of the interactive knowledge being more than the sum of the theoretical and the practical knowledge, and Malmberg (2007) talks about engineering knowledge being more than just practical knowledge (*techné*) and theoretical knowledge (*episteme*) due to the choices that has to be made (*phronesis*). We show that a conceptual object consists of both concepts and things to do with them, and that building a coherent body of understanding a whole, a composite concept or here called a complex concept, amounts to make links between the parts, the isolated concepts. We also notice that when a concept is already learned it may have merged into one concept, and that recognising parts in it is not always easy to do, the concept has become a taken-as-given.

In a report from part of a large European study (the LSE-project), carried out in six countries, Tiberghien et al. (2001, p. 502) notes in her conclusions that "In all disciplines, there are striking patterns with regard to what the students have to do and what they are *not* asked to do during labwork. At secondary school, the students often have to make direct reports of observations, but they do not often have to present or display or make an object. They seldom have to explore relationships between objects, test a prediction, choose between two (or more explanations), or invent a new concept (or entity)." In our research we have found that it is not only important to explore the relationships, rather it amounts to do the actions that form the relationships. In the final report on the LSE-project Psillos and Niedderer (2002) sadly neglect the last point Tiberghien makes in her report (Tiberghien et al., 2001)in the above citation, that students seldom are asked to choose between explanations. However, this resonates well with Malmberg's findings (2007) that phronesis, the knowledge that lies in the making of choices is an important aspect of knowledge. In our research the students need to choose the two relevant functions among all previously learned mathematical functions, to realize that only two types are relevant for transient responses, although other functions may be more common and relevant in other parts of as well mathematics as engineering. Since the lab-instruction is ruling what students do (Tiberghien 2001) it is important to instruct student to make choices, but as shown in this research it is also necessary to facilitate for students to make these choices. Just to ask the students to choose the appropriate function was not enough. In the old course the students were shown one function (in the time domain), and were asked to choose the relevant appropriate function to fit to the measured one, but before doing calculations there were too many functions to choose from. By simulation of some possible curves, the students were able to engage in the necessary calculations and from those, choose appropriate functions for the curve fit. To learn how to experience the critical aspect is the main point discussed by Baillie, Bowden, and Meyer (2013), and is a significant thread to unravel in future work.

To notice that the functions have to be solutions to differential equations, and thus exponential and that second order systems always give either the damped sinewave or two added exponential functions, are *critical aspects* from the theory/model world that needs to be linked to the experimental graph in the object/event world. To facilitate for students to choose these functions among the repertoire of possible mathematical functions is to help the students also with the knowledge Aristotle names phronesis.

The choice to use the model of the two worlds rather than the traditional theory-practice divide, makes it possible to see why the interactive knowledge (Ryegård, 2004) is more than just the sum of the theoretical and practical knowledge. Theoretical is more than conceptual, and practice is more than procedural, and adding the two is more than the sum due to choices that as well constrain which possible choices from the repertoire that are possible to choose from as opens up for seeing the whole.

Eckerdal describes in an ongoing project the need to "investigate the complex interplay between learning of theory and learning of practice in computer programming through laboratory work" (Eckerdal, 2012), since earlier research has focused on either learning of practice or learning of theory. One early finding in this project is that learning "requires that students can discern the meaning of the practice they perform and the theory that relates to this practice," (ibid.) and argues that lab exercises can be designed in such a way that learning of theory and learning of practice during the lab session support each other mutually." (ibid.) This interplay is what we also found to be the most difficult links to make, although, the traditional divide may obscure what this relationship is.

10 Conclusion and Implications for further research

10.1 Conclusions or rather – Openings made possible through research

The purpose of this thesis was to investigate learning in an electric circuit course by means of modelling the learning process. The research proposition was:

- to develop a model: The learning of a complex concept
- show how this model can be used as well for analysis of the intended object of learning as students activities during lab-work, and thus the lived object of learning
- use the model in analysis of what changes in instruction that are critical for student learning.

10.1.1 To develop a model: The Learning of a Complex Concept

We have developed a model and shown that in the case of transient response it has been a useful tool to as well find as analyse critical aspects. To have *making a model* as one of the research propositions, makes several steps in the research process come in already as part of the study. Since a model always needs to be tested and refined, such issues as validity come in very naturally, here through the four different studies. Also a triangulation is made by analysing the data by using several theories and methods. When the model is tested with different methods, even from different philosophical viewpoints, and still the model holds sway, also a triangulation is made.

Modelling is the most fundamental enterprise in engineering, maybe, even that modelling is engineering[31] to paraphrase Mitcham (1994, p. 220). To choose the method of modelling was therefore the most evident method to use. The importance of modelling can be attributed its power to *show functionality*, *predict future behaviour* of a *system.* In this study to *function as a tool*, and *predict learning pathways,* when learning *a complex concept*, *a system of objects of learning*. The validation of the model is then to, put the model into practice, and see if the results were the expected, or maybe even exceed the expectations, as they did in this study – the new discourse in the new course certainly did exceed our expectations.

The model can show what students are learning or not learning, what students are intended to learn and how instructions may be changed, i.e. *the lived object of learning, the intended object of learning* and *the enacted object of learning.* The model has already been used in another study, where critical aspects of frequency response, an equally complex topic and equally important topic for engineering students to learn was in focus (Bernhard, Carstensen,

---

[31] cf. the discussion in 3.6 Towards a philosophy of Technology

& Holmberg, 2010, 2011). As Knuuttila (2011, p. 264) puts it: A model is judged by "success rather than accuracy", or in words of (Cobb et al., 2003) by the work they do.

The model has been the focus of all the studies presented in this thesis, and has been developed, evaluated in terms of predictability and analysed in several ways.

10.1.2 Show how this model can be used as well for analysis of the intended object of learning as students' activities during lab-work, and thus the lived object of learning

The model was used for analysis of students' activities two different years, 2002 and 2003. By using the same instrument for the analysis it was possible to see what differences in students' lived object of learning were related to the changes in instructions. To relate the three objects of learning – *the lived object of learning, the intended object of learning* and *the enacted object of learning,* and do that by using the same tool, the model *learning of a complex concept*, it was possible for the researchers to link the results from different studies, thus make links, thus learn, what was critical for students to learn. Thus also the learning path for the researchers included making links – links between methods, links between objects of analysis. Although in this research called concept, the object of learning includes as well objects in the *theory/model world*, *episteme*, objects in the *object/event world*, *techné, making links* between them, and *how* to make links, *phronesis*. As well for the students as for the researchers, the learning included to choose among possible ways to link objects from the two worlds.

The issues of how to learn includes as well *to make links* as *how to make links*. The term *learning of capabilities*, was founded by Bowden and Marton (1998) several years ago, and concerns how to learn to experience, how to learn to discern critical aspects in order to see the variation. This has been highlighted in recent research in engineering education: "There is a need for learning experiences that help individual students develop judgment (*phronesis*) or discernment—discerning the relevant aspects—and also the capacity to follow through with successful solutions (includes *episteme* and *techné*)." (Baillie et al., 2013, p. 234)

Although touched upon in the above studies there is more to analyse in this respect, especially concerning linking the three knowledge types – *episteme, techné* and *phronesis*.

10.1.3 Critical aspects of learning – use the model in analysis of what changes in instruction that are critical for student learning –

In order to learn the student needs to discern specific features of the phenomenon to be learned. Not all features of a phenomenon have to be discerned, but those that are critical for a certain view have to be discerned and brought into the student's focal awareness. In the model described in this work one can argue that not all aspects are described, but that is characteristic of every model. The very purpose of a model is to show some carefully chosen aspects and highlight those that are relevant – "There is no complete, final description of anything and our descriptions are always driven by our aims." (Marton & Booth, 1997, p. 123) In this work the aim with the model is to show those aspects that show what students do and not in relation to the intended object of learning. A complex concept, is a composite concept, which consists of a part/whole-relationship that is not just a simple relation between objects, but a whole range of links, that have to be made, and made in a manner that makes up this web. There may be objects that are not possible to link through a single link, but that necessarily are linked through a route of more than one link, as in the case of linking the graphs to their mathematical representation.

Our work has tried to meet the challenge that was highlighted in the ETL-project (mentioned above in Chapter 5), that there are typical "ways of teaching and practicing" (Entwistle, 2005, p. 5) and that students

> "are faced with contrasting representations or models of a circuit - the actual circuit, the circuit diagram, simplifying transforms of it, algebraic solutions, and computer simulations. Students have to move between these different representations in solving problems or designing circuits and they also need to understand the function of a circuit in both practical and theoretical ways – the engineering applications and the physics of how it behaves." (Entwistle, Hamilton, et al., 2005, p. 9)

By making the model we could highlight what it takes to move between these different representations, to make the necessary links, but also to change the pathways students take, so that they make necessary links. Thus we used

- Links as tool for analysis of gaps – Links as tools for analysis of lived object of learning
- Links as tools for analysis of critical aspects – Links as keys for opening up possibilities to make a new enacted object possible

Since critical aspects often become taken for granted once something is learned it can be rather difficult to find the critical aspects for learning. Often research into critical aspects has shown that even the scientific view was ambiguous in meanings and that the research not only contributed to the educational field, but also to their scientific fields (e.g. Davies & Mangan, 2008; Malmberg, 2007; Renström, 1988; Strömdahl, 1996). To do research on critical aspects reveals what there is to learn, i.e. gives knowledge of the concept itself, not just knowledge of how students learn.

To view the calculated and the measured graphs as two different concepts, and not as one, which teachers normally do, was a critical aspect for the researchers to notice. As Tiberghien (e.g. Becu-Robinault & Tiberghien, 1998; Sensevy et al., 2008; Vince & Tiberghien, 2002) has pointed out for over ten years – modelling the intended object of learning through analysing *the model of the lived object of learning* is a fruitful analytical tool in designing teaching sequences and lab-instructions.

We have also pointed out that keys and thresholds are not the same, although of course related. In the studies reported in this thesis, the transient response is the threshold concept that we want the students to learn. It is difficult to learn, *troublesome*, but it also demonstrates the other features of a threshold concept, when *learned* being *transformative, irreversible, and integrative.* Still to just find the thresholds, which are rather easily found, it is also necessary to find out what is critical to learn, what might be a *key* to open the portal, to pass over the threshold. The key here is to find options for students to anticipate the solutions to the calculations they need to make, as well in order to be able to see what function to use in the curve fit-procedure, but also in order to enter the liminal space, and start doing the calculations. Thus the key is the set of simulations that the students are asked to do.

It is important to notice the use of key concept here

> "We use the term as a more precise metaphor to mean that the concept in question acts like a key to *unlock* the 'portal' of understanding, the 'portal' which opens up for learning of other concepts" (Carstensen & Bernhard, 2008, p. 143), and "not in the sense that the term is often used in some educational contexts, as interchangeable with 'core' concepts, and meaning simply that the concepts are an important part of the prescribed syllabus." (ibid.) (citation from 4.4 above)

A key is not the foundation that a building is constructed upon; it is what you use to open the door. 'Core concepts' are the building blocks, fundamental for building a discourse or syllabus, and the 'key concepts' make it possible to enter the building.

10.1.4 Towards answers to the original questions

To some extent also the original research questions were possible to answer:

- how students work with lab-tasks, especially concerning the goal to link theory to the real world
- how it is possible to change the ways students approach the task and thus their learning, by systematic changes in the lab-instructions

A brief analysis of the difference in discourse in the old and new courses can be illustrated through the table below:

2002	2003
One curve at a time	Relations between curves
Math as late as possible – When pointed out to be necessary	Math and simulations – From the beginning
One island in the circle at a time	Making links between islands throughout the lab
Discussion of process	Discussion about content
Is this good enough for the report?	Know what they are doing

Table 10: Different discourse in the new course

10.2 Implications for further research

I have chosen to highlight four interesting threads to unravel. The first one is a direct continuation of the research in this thesis. The two following are areas very interesting, but belonging in other research domains than mine. The reason to lift them here is that the examples from the transcripts are so demanding, that I could not just put them aside. The fourth and last is the one which is opening up for new interesting areas of research, where both methods and results from this work will be a good starting point for further research.

10.2.1 Follow up studies on related topics

There are of course several issues to study further. Some of those I have already mentioned, e.g. the studies of (Bernhard et al., 2010, 2011). In these the threshold concept frequency response, is studied, and two critical aspects have been highlighted, Bode Plots (Carstensen & Bernhard, 2002) and to learn phase shift (Bernhard, Carstensen, & Holmberg, 2013). In both of these, as well as in the studies presented above, the link between graphical representations and the mathematical calculations have proven to be keys for students. Frequency dependency in engineering is dealt with in many different ways in the different subjects. Some aspects are general such as amplitude, phase shift, differential equations, Fourier series, complex numbers, but there are also more subject specific aspects, such as reactive components in electric circuits, amplification and feed-back in control engineering and analogue electronics. These specific topics have also rendered different ways to draw the graphs, e.g. using f or ω as the frequency axis, or *dB*-scale on the vertical axis or not. Such subtleties are often confusing for students, and raises the question whether it is possible to find ways to learn these aspects as more general capabilities or need to be dealt with in each subject where they are applied, as is often the case today. To investigate how capabilities relate to content, would be a very interesting follow-up study to carry out.

10.2.2 Language and Learning

One aspect that has been brought up, but not further investigated in the studies above is the use of language. We have e.g. seen that the teachers sometimes do not reflect on whether they are discussing Voltage or current. The simulations that students are asked to carry out regard the Voltage output, whereas the calculations regard current. Since the computer tool can show both this does not seem to be a problem, but is it? Another is the use of “correct” terms when dealing with the mathematical content. In the new course even the students say differential equation, when they talk about the transfer function. In the two last turns of the transcript below, Chris says “differential equation” and Tess replies “you have to inverse-transform it”:

```
2003_Group_1 _Tape_1 25:18
Benny: Alright, it's just to do as it says here then, but
       have we've gotto calculate, What's the use
       of calculating when the computer has already done it?
Chris: You can't sit here and calculate what it will look like
Tess:  What?
```

(raises from her calculations)

Chris: Calculate the step response
Tess: Yes you can
Chris: We have a differential equation for how this circuit will
behave over time
Tess: Yes, but only when you have inverse-transformed it you
will get it back

Here it is obvious that although Chris says differential equation, as well he as Tess know that it is the Laplace expression he is talking about.

When is the use of appropriate language necessary, and when is the use of non-scientific language rather showing that the students now know what they are talking about, by the very use of the non-scientific expressions?

10.2.3 Gender issues in engineering

When I started this research work I was engaged in a project that was dealing with gender issues in engineering education. Why do so few female students enter electrical or control engineering? Why do female students quit in proportionally greater numbers? These questions have not at all been in focus of this research, but I cannot avoid noticing one specific instance in the transcriptions that caught my interest, namely a passage where a female students asks a fellow student for help, the male student does not answer her, but instead claims that he doesn't know whether his calculations are correct:

2002_Group_22 _Tape_3 3:34

Girl: Are you doing the 33 ohm Moves her eyes
towards Jocks pad

Oh you sit here and do calculations,
You asshole. How do you do that?
Jock: Don't know=
Girl: You don't know how to calculate
Andrew: He doesn't know
Jock: Well, ah, well I don't know how to get this one (.) so one has
to
calculate in order to find out what it looks like
Girl: But how do you calculate it then?
Jock: Well you run the transfer function an' Laplace

(laughs and ... his
shoulders)
Girl: Show me
Jock: But I don't know how to (all three laugh)

```
Jock: If I get it right I'll show you
Girl: Isn't it just weird that you have to sit here and just press
      buttons
      for two hours
```

The female student leaves the group and goes back to her own place, very disappointed that she doesn't know how to do the calculations knowing she needs to do them in order to be able to go on with the lab task. Interestingly another student approaches the same group and asks the same question, and although the answer still is that Jock doesn't know the answer, he lets the male student join in. Not until he has succeeded he turns to the female student.

Although I have not focussed this in my research, I have noticed similar situations. Again a new research area, which I suggest as interesting for future research.

10.2.4 Learning of Complex Concepts

One of the questions we were asked at conferences in education was "Why do you still teach Laplace transforms, when it is so difficult?" Although we have already tried to give an answer in section 2.1 "Why do we teach this mess?", this issue may be interesting to revisit. In our research we have found that it is possible to reduce the difficulties students have with the topic, not by simplifying it, but by actually adding one new topic, simulations (even introducing one more computer program than in the old course). This issue is also dealt with in regard to *capability theory*: "The work on troublesome knowledge after Perkins (1999) suggests that when teachers simplify a difficult concept to make it easier for students, they can make it even more difficult for students later on to re-learn the true complexity of the concept. Simplification is not good pedagogy." (Baillie et al., 2013, p. 234)

In my view it is not to avoid the problems that makes an engineer, but to work jointly to find solutions. Thus to keep on exploring students' difficulties (or maybe rather teacher difficulties in facilitating for students), especially regarding complex concepts is the implication, from this work, for further research.

One such opening is to take criticism, not as critique, but as openings for further research. In electrical engineering research we have had a couple of such discussions, one already dealt with in the review of previous research, one will be dealt with here.

Kautz (2011b, p. 1) raises an interesting starting point for investigation:

> "Interestingly, it appears as if in this case it is not a lack of connection between model and real-world objects that causes difficulties for many students, as suggested by Carstensen et al. (2005) in the context of a lab activity on transient behavior of electric circuits. Instead, students may make too close a connection between the graphical representation of the mathematical formalism and the real-world objects to which they (incorrectly) ascribe certain properties."

I would argue, that it is quite the opposite: Since the students have not yet linked what they see in AC-labs (the phase-shift when measuring the voltage and current of the source) to the theory, the theoretical assumption they make, that ideal sources have no phase difference is possible for them. Since an ideal source does not include any reactive elements, and the model the students use most easily is Ohm’s law, they assume that this theory is enough to judge the behaviour of the source. However, models are only applicable within certain constrains, the “*domain of validity*” (Ljung & Glad, 1994, p. 17), and this is something students may not be aware of. Problems like local reasoning, applying AC-circuit to transformers although attached to a DC-source, assuming ideal sources to have voltage and current in phase or that there can be no current without voltage are all examples where students have not yet appreciated the *domain of validity* of the theories they apply, and thus they do not make links to what they can experience in the object/event world. When students get the so called “Conceptual questions” in exams, they often feel that these are traps. For example, students have never met transformers in a situation where DC is applied, so why would they consider using knowledge from that domain in a question about transformers? In the case of local reasoning, it seems to me that to model the links between the theoretical constructs that students need to link, such as Ohm’s and Kirchoff’s laws, and different circuits, as well DC- as AC-circuits would be a way to “Facilitate Linking Models and the Real World through Lab-work in Electric Circuit Courses for Engineering Students” (the title of this thesis)

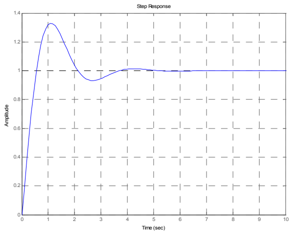
10.2.5 Endnote

Now that I have come to the end of the book, still there is much more to do, to learn, and to explore. The comfort is that there are no conclusions in learning – only new openings. The probably most important key to learning is to go on learning, opening up for new views, new itineries.

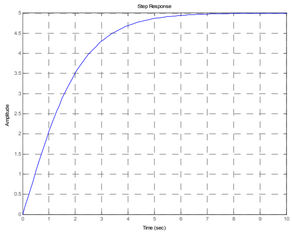
11 Appendix

11.1 Appendix1: Examples of systematically varied Laplace-functions to analyse, mathematically and graphically

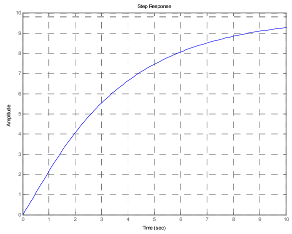
$$G(s)=\frac{2s+5}{s^2+2s+5}$$



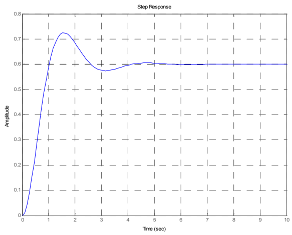
$$G(s)=\frac{2s+5}{s^2+2s+1}$$



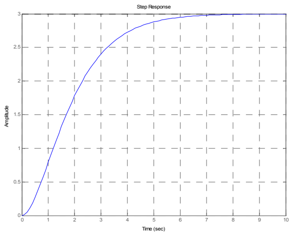
$$G(s)=\frac{2s+5}{s^2+2s+0.51}$$



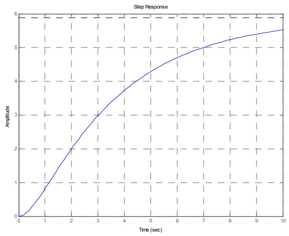
$$G(s)=\frac{3}{s^2+2s+5}$$



$$G(s)=\frac{3}{s^2+2s+1}$$



$$G(s)=\frac{3}{s^2+2s+0.51}$$



Important characteristics:

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

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

gives under-critically damped behavior

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

gives critically damped behavior

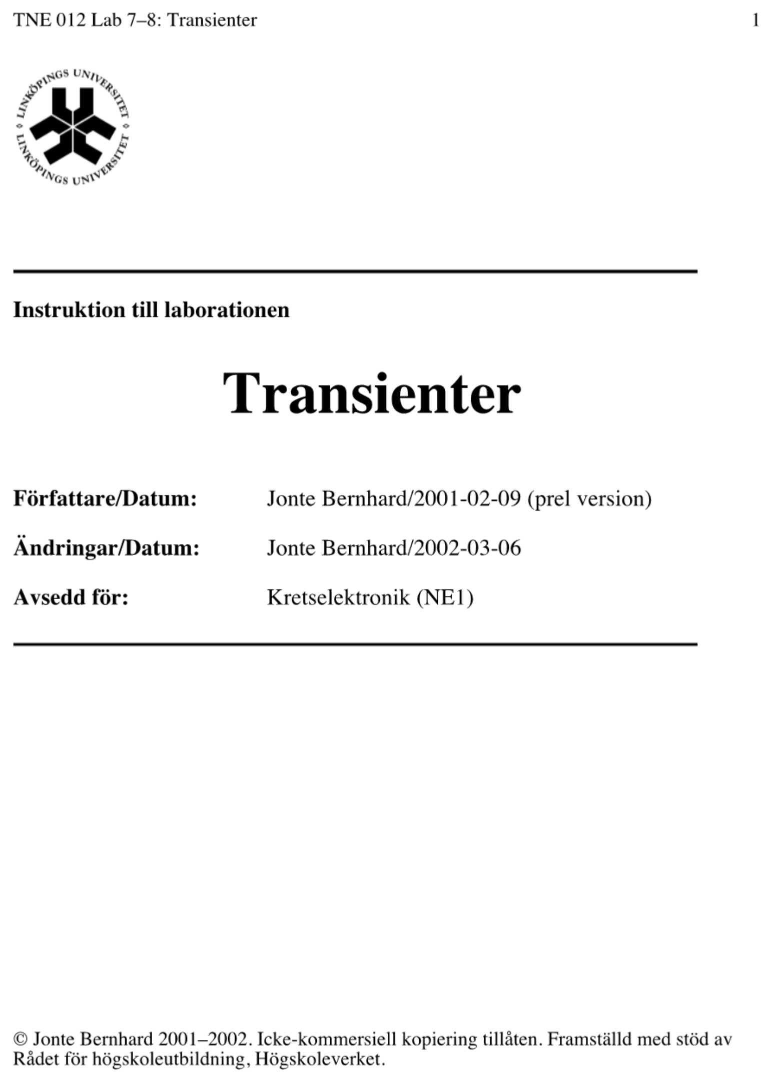
$$s=-1\pm\sqrt{1-0.51}$$
$$s_1=-1+0.7=-0.3$$
$$s_2=-1-0.7=-1.7$$

gives overcritically damped behavior

2) Note the different start behavior that depend on the difference in degree of powers in the nominator and denominator polynomials

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

11.2 Appendix 2: Lab-Instruction 2002



Instruktion till laborationen

Transienter

Författare/Datum: Jonte Bernhard/2001-02-09 (prel version)

Ändringar/Datum: Jonte Bernhard/2002-03-06

Avsedd för: Kretselektronik (NE1)

Transienter

1. Inledning

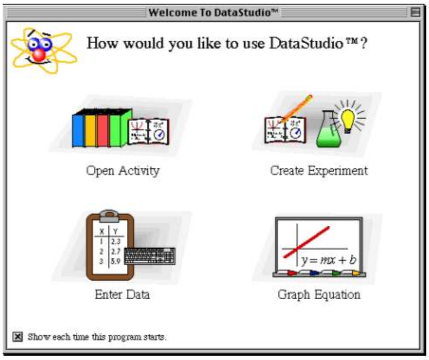
I denna laboration skall ni undersöka stegsvaret hos en RLC-krets för några olika kombinationer av R, L och C. Som mätutrustning skall ni använda ett system med s k mätdatorinterface anslutet till en dator. I ett sådant system styrs insamlingen och bearbetningen och presentationen av experimentella data från datorn. Interfacet omvandlar signalen från olika givare (synonymt namn för givare är sensorer) för mätning av temperatur, spänning, ström, pH m m till en form som förstås av datorn. Det interface som vi kommer att använda (PASCO ScienceWorkshop 750) har även en inbyggd funktionsgenerator som även den styrs av datorns programvara. Detta interface, med tillhörande programvara, är speciellt utvecklat för undervisningsändamål, vilket gör att det är lättare att komma igång med. Mer professionella program och utrustningar är kraftfullare, men i gengäld är bl a inlärningströskeln i regel högre. System där datorn utnyttjas för styrning av och behandling av data från mätinstrument och mätsystem har utnyttjats inom forskning och utveckling under några decennier och får större och större betydelse.

2. Start av programmet DataStudio

Nedan följer en kort beskrivning av några funktioner i programmet DataStudio och interfacet ScienceWorkshop 750. Beskrivningen är dock inte heltäckande. Fler funktioner framgår av menyer och hjälpfiler. Vissa marginella skillnader finns också mellan denna instruktions skärmbilder och det ni ser på datorskärmen p g a skillnader i datorsystem.

Interfacet ScienceWorkshop 750 är ansluten till datorn via s k SCSI (det är möjligt att ansluta detta interface också via serieporten, men för de försök vi ska göra ger detta för låg snabbhet) för att kunna föra över data med hög hastighet till datorn. Därför måste interfacet vara anslutet till datorn via SCSI innan datorn startas.

1. Slå på strömmen till interfacet och starta därefter programmet DataStudio. Ni skall då se en bild liknande den till höger. Klicka på `Create Experiment`.



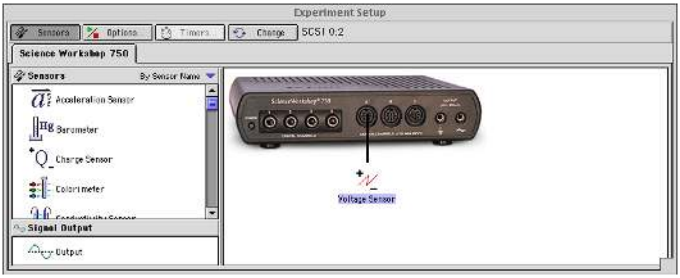
Welcome To DataStudio™

How would you like to use DataStudio™?

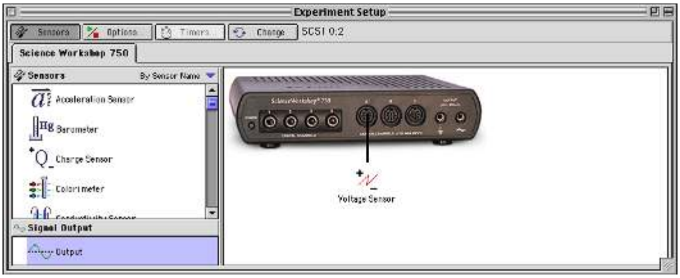
☒ Show each time this program starts.

Ni får då upp nedanstående bild. Programmet måste veta vilken/vilka givare som är eller kommer att bli anslutna till interfacet. Dubbelklicka på `Voltage Sensor` (alternativt “dra” den till analog ingång A).

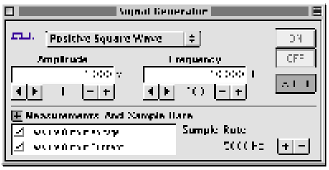
Efter angivandet av `Voltage Sensor` ska ni ha fått nedanstående bild.

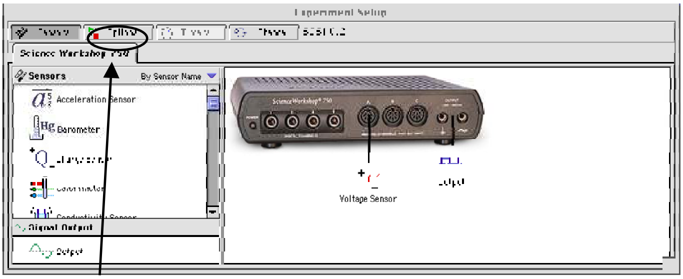


Vi ska också använda interfacet som funktionsgenerator. Klicka därför på `Output` enligt bilden nedan.



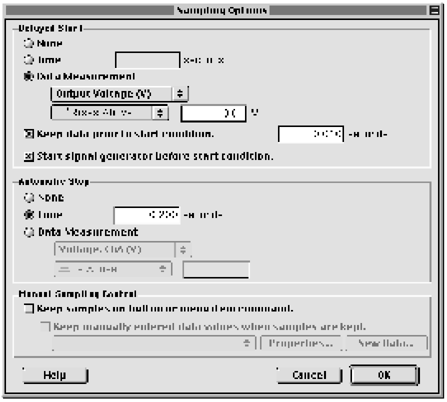
Ni får då fram inställningsfönstret `Signal Generator` som styr funktionsgeneratorn. För att efterlikna steget används `Positive Square Wave`. Denna bör då ha en frekvens som gör att dess periodtid är väsentligen längre än de transienter som vi skall studera. Lämpliga värden att starta med är 10 Hz för `Frequency` och 1 V för `Amplitude`. Vi skall också ställa att såväl utspänning som ström skall mätas. Klicka därför på plustecknet vid `Measurement And Sample Rate`. Markera därefter såväl `Measure Output Voltage` och `Measure Output Current`. Detta fönster ger också möjlighet att `Sample Rate`. `Sample Rate` (Samplingsfrekvens) anger hur många mätningar som tas per sekund. Valet av samplingsfrekvens är alltid en balansgång mellan olika krav. Hög samplingsfrekvens belastar bl a datorn och mätsystemet men kan ge mer detaljer. Låg samplingsfrekvens ger mindre med data att bearbeta, men kan medföra att man inte ser de detaljer man behöver se. I detta fall kan det vara lämpligt med 5000 Hz. När ni är färdiga skall det se ut enligt nedan.





Slutligen kan man välja att låta programmet automatiskt starta och stopp mätningen. Eftersom det är frågan om snabba förlopp med hög samplingsfrekvens är detta särskilt lämpligt. Klicka på `Options`.

Ni får då fram ett fönster enligt nedan. Lämpliga inställningar syns i fönstret.



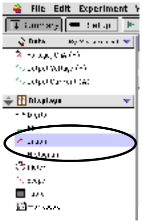
Sampling Options

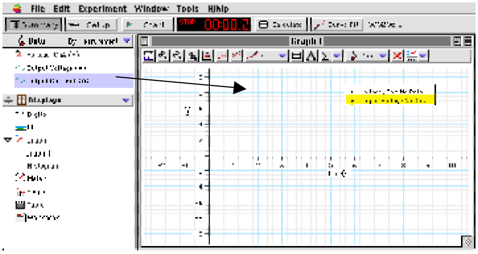
Delayed Start
○ None
○ Time [illegible]
● Data Measurement
Output Voltage (V)
[illegible] [illegible] V
☒ Keep data prior to start condition. [illegible] seconds
☒ Start signal generator before start condition.

Automatic Stop
○ None
● Time [illegible] seconds
○ Data Measurement
Voltage, ChA (V)

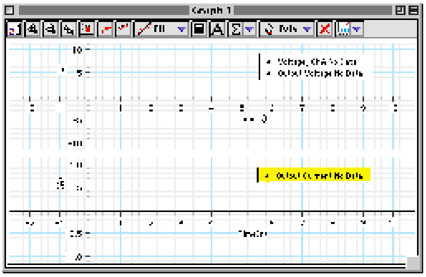
Manual Sampling Control
☐ Keep samples on button or menu item command.
☐ Keep manually entered data values when samples are kept.

Slutligen ska vi bestämma hur resultaten ska visas. Detta görs lämpligtvis i form av en graf. Dubbelklicka på `Graph`. Grafen kommer då endast visa `Voltage, ChA No Data`. För att få med `Output Voltage` och `Output Current` “drar” ni dessa till grafen och “släpper” .





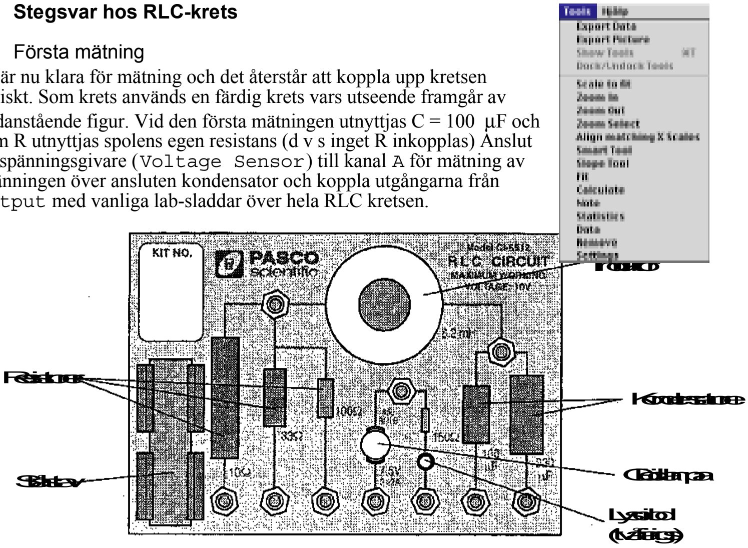
Grafen skall då se ut enligt nedan. Det är lämpligt att ordna så att grafen blir större.



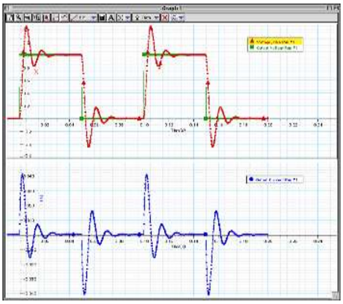
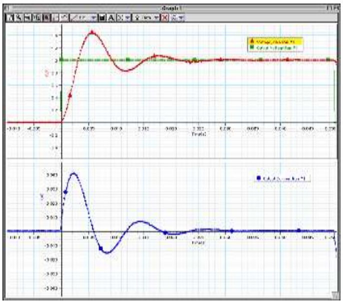
3. Stegsvar hos RLC-krets

3.1 Första mätning

Vi är nu klara för mätning och det återstår att koppla upp kretsen fysiskt. Som krets används en färdig krets vars utseende framgår av nedanstående figur. Vid den första mätningen utnyttjas C = 100 µF och som R utnyttjas spolens egen resistans (d v s inget R inkopplas) Anslut en spänningsgivare (`Voltage Sensor`) till kanal `A` för mätning av spänningen över ansluten kondensator och koppla utgångarna från `Output` med vanliga lab-sladdar över hela RLC kretsen.



Vi är nu klara för mätning. Starta mätning genom att klicka på knappen `Start` i DataStudio. Om allt fungerar har ni nu fått en graf liknande den nedan till vänster. Som alltid är det lämpligt att nu spara (`Save Activity`).

Denna figur kan nu skalas om för att få fram själva “stegsvaret”. Denna skalning kan ske på olika sätt: Man kan dubbelklicka i figuren och få fram möjligheten att ställa in skalor på axlarna, man kan utnyttja zoom-verktyget eller man kan “peka” nära någon siffra på en axel och “dra”.

Figuren kan antingen skrivas ut med vanligt `Print` kommando eller exporteras . För export utnyttjas `Tools/Export Picture`. Denna bild kan sedan infogas i Word genom kommandot `Infoga/Bildobjekt`.

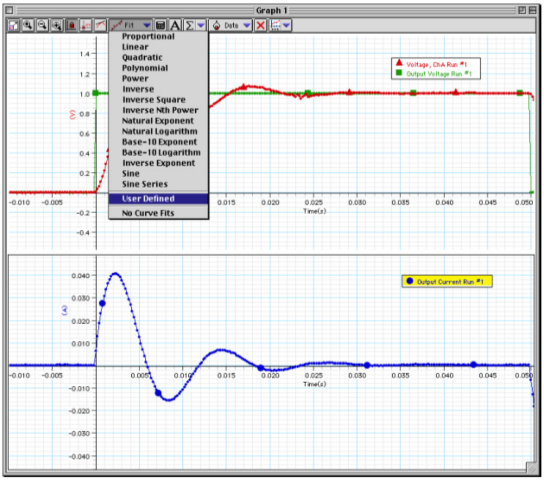
3.2 Ytterligare mätningar

Mätningarna upprepas med samma värde på L och C men med R = 10 Ω, 33 Ω respektive 100 Ω. (Observera punkten om bearbetning nedan. Ni avgör själva om ni gör bearbetningen efter varje mätning eller mäter först och bearbetar sedan.) Vilka skillnader observerar ni?

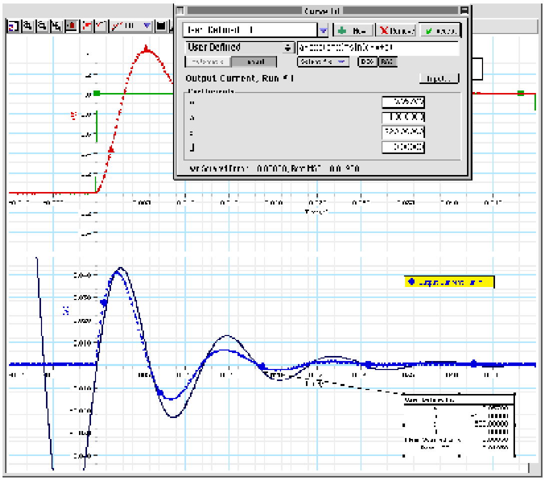
Genom att sätta in järnkärnan i spolen ungefär fördubblas dennas induktans. Gör detta och upprepa mätning med dels R = R_{spole} respektive 10 Ω. Vad observeras? Slutligen tag ur järnkärnan och använd R = R_{spole} men använd C = 330 μF.

3.3 Bearbetning

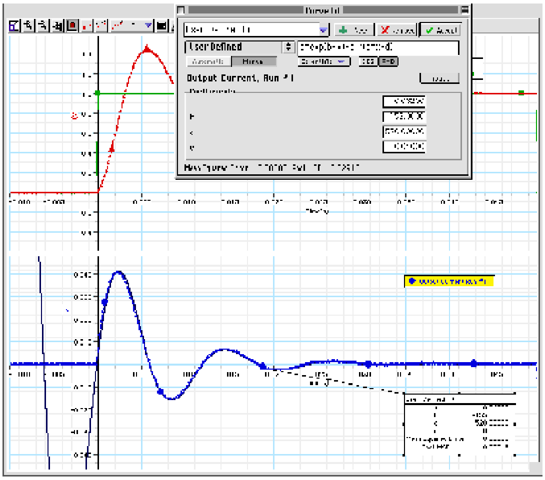
Mätning med datorinterface innebär att data finns lagrade och kan exporteras till Excel eller annat program för vidare behandling. DataStudio-programmet innehåller en möjlighet att göra en s k `Fit` (anpassning) till experimentella data. Nedan visas en anpassning av uppmätt ström genom kretsen till en dämpad sinus. Då denna inte fanns med bland de färdiga funktionerna har `Fit/User Definied` valts.



Nedan visas inmatningen av en dämpad sinus i `User-Defined Fit`. Värdena ändras manuellt tills en så bra anpassning som möjligt erhålls. Vid anpassningen nedan är man inte riktigt framme. Prova att ändra de olika konstanterna för att få en känsla för vad de står för. Vad innebär ett stort eller litet värde?



Här har man fått så bra anpassning som är möjligt vid en manuell anpassning.

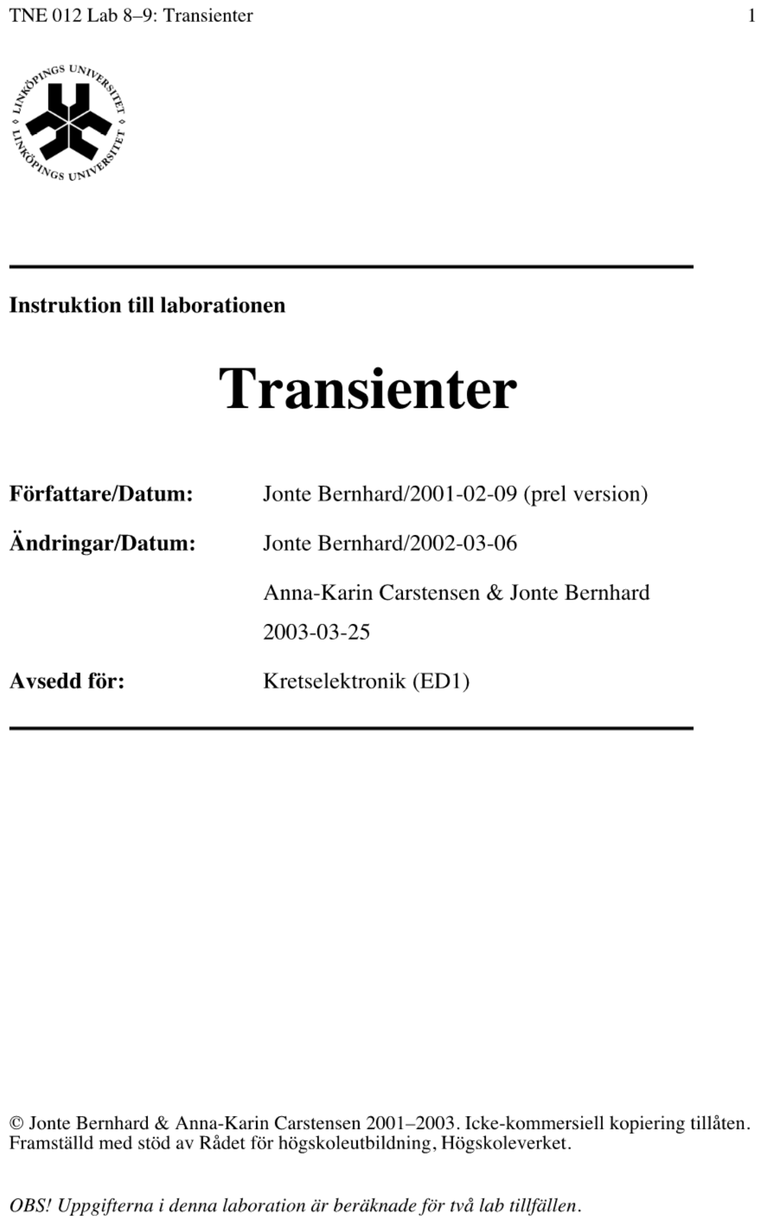


Ni skall göra anpassningar för strömmen för mätningarna med L och C konstanta (8,2 mH respektive 100 μF) men med olika R = R_{spole}, R = 10 Ω, 33 Ω respektive 100 Ω. Utifrån de anpassningar ni får skall ni beräkna vilka värden på R, L och C detta motsvarar (kräver att ni löser uttrycket för strömmen med t ex Laplace). Observera att beroende på vilket värde som R har så kommer lämplig funktion att anpassa till att vara olika.

4. Redovisning

Laborationen redovisas genom en s k fullständig rapport per grupp. Denna ska innehålla en kortfattad beskrivning av försöket, figurer från mätningarna och anpassningarna (behövs ej separat figur utan anpassning för de fall som en anpassning görs). Det skall framgå vilken funktion som ni har anpassat mot och vilka värden på R, L och C som anpassningen motsvarar. Skillnaderna mellan de olika resultaten skall beskrivas samt också förklaras utifrån teorin. Figurerna kan antingen bifogas från direkt utskrift från DataStudio eller genom att dessa har infogats i ett ordbehandlingsdokument.

11.3 Appendix 3: Lab-Instruction 2003 – After changes:



Instruktion till laborationen

Transienter

Författare/Datum: Jonte Bernhard/2001-02-09 (prel version)

Ändringar/Datum: Jonte Bernhard/2002-03-06

Anna-Karin Carstensen & Jonte Bernhard
2003-03-25

Avsedd för: Kretselektronik (ED1)

Framställd med stöd av Rådet för högskoleutbildning, Högskoleverket.

OBS! Uppgifterna i denna laboration är beräknade för två lab tillfällen.

1. Matlab och Simulink för att göra beräkningar med Laplacetransformer.

Det vi framför allt ska arbeta med under denna lab är överföringsfunktioner uttryckta mha Laplacetransformen, och simulera hur t.ex. stegsvaret ser ut för olika överföringsfunktioner. Vi kommer senare även att använda Simulink och Matlab för att undersöka frekvensgången för elektriska kretsar.

Vi kommer att arbeta omväxlande med beräkningar för hand och beräkningar mha Simulink.

Om vi har en överföringsfunktion för en krets skriven mha Laplace-transformen t.ex.:

$$G(s) = \frac{V_{ut}}{V_{in}} = \frac{c}{s^2 + as + b}$$

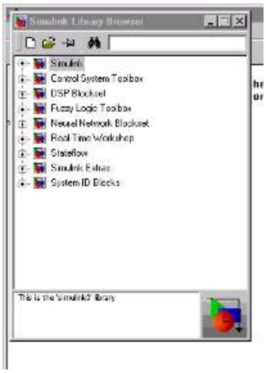
så fås stegsvaret genom att beräkna tidsfunktionen för $\frac{1}{s} \cdot G(s)$. Vi kan även använda blocken *step* och *transfer function* i Simulink för att göra motsvarande beräkning i Matlab.

1.1 Introduktion

Starta Matlab.

Starta Simulink genom att klicka på Simulink-symbolen på verktygslisten:

Du får då tillgång till Simulinks biblioteksfönster, där du via menyraden kan välja att öppna ett nytt dokument, dvs öppna ett nytt fönster där du kan rita en Simulinkmodell eller öppna en befintlig modell (.mdl-fil). Här får du även tillgång till Simulinks komponentbibliotek :



This is the 'simulink3' library

I katalogen Simulink finns t.ex.:

Sources: t.ex. Step input, Sine wave

Sinks: Scope, XY-Graph, etc.

Discrete: Komponenter för tidsdiskret reglerteknik eller elkretsteknik

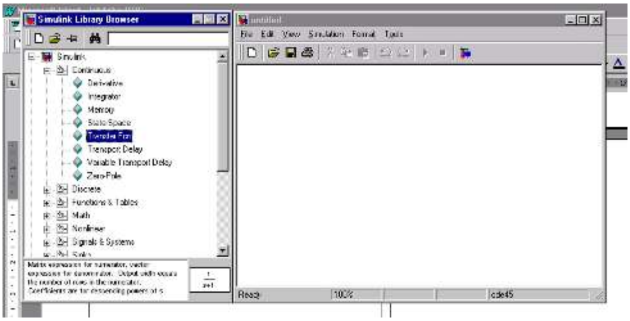
Continous: Linjära komponenter, t.ex. Förstärkare, Överföringsfunktioner, Summeringsfunktioner, Integratorer

Nonlinear: Produkt, Gränsvärden, etc.

Connections: Mux, In, Out

Math: Absolutbelopp, Trigonometriska funktioner, Gain etc.

Klickar du på symbolen för nytt dokument (vita rutan högst upp till vänster) öppnas en ny simulink-modell , dvs ett fönster där du kan rita din modell:



Matrix expression for numerator, vector expression for denominator. Output width equals the number of rows in the numerator. Coefficients are for descending powers of s.

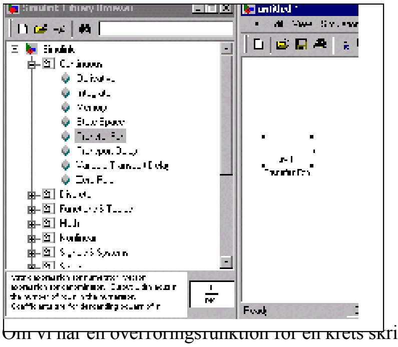
$\frac{1}{s+1}$

Se till att du kan ha både Simulinkbiblioteket och din egen modell öppna samtidigt, du kommer annars att behöva bläddra mellan fönstren. (Ett sätt att alltid ha Simulinkbiblioteket synligt är att klicka på symbolen

📌

som gör att simulinkfönstret alltid ligger överst bland de aktiva fönstren.)

För att hämta komponenter ifrån biblioteket klickar du på en komponents namn, drar med musen in komponenten i din modell, och släpper. När du t.ex. klickar på "Transfer Function", visas en kort förklaring, samt den figur som kommer att klistras in i din modell (I figuren ovan "Untitled"). Drar du i den markerade texten (Transfer function) med musen, klistras symbolen in i modellfönstret.



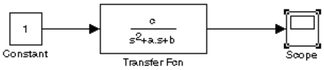
Om vi har en överföringsfunktion för en krets skriven mha Laplace-transformen t.ex.:

$$G(s)=\frac{V_{ut}}{V_{in}}=\frac{c}{s^2+as+b}$$

så kan vi använda blocket transfer function och simulera stegsvaret.

Ta blocket Transfer Function ur biblioteket Continous:

Dubbelklicka på symbolen för att få se och ändra parametrar för blocket. Här du ska du föra in koefficienterna från överföringsfunktionen på matrisform, dvs. i täljaren c, och i nämnaren koefficienterna 1 a och b: [1 a b] dvs koefficienten framför s^x-termerna, så att koefficienten för högsta x, här s^2 , kommer först.

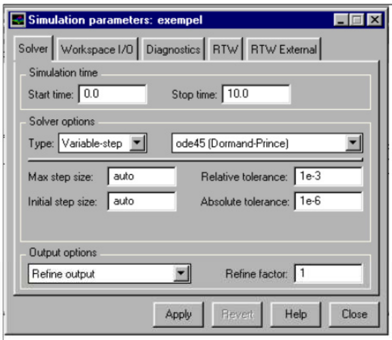


För att knyta ihop blocken markerar du vid in-pilen på en komponent, drar med musen till föregående komponent, och släpper vid dess ut-pil.

Vi ska nu simulera stegsvaret, dvs lösa diffekvationen då $x(t) = \begin{cases} 1, t \geq 0 \\ 0, t < 0 \end{cases}$.

Blocket ”Step” ger en sådan funktion, men där kan man välja starttid. Starttiden är förinställd, så att x blir 1 vid tiden t=1, men vi ville ju välja t=0. Dubbelklicka på ”Step”. Välj step time till 0. Stegets storlek vill vi ju ska vara 1, och ursprungsvärdet före tiden t=0 ska vara 0, dvs vi behåller de förinställda värdena.

Vi startar simuleringen genom att på menyn välja ”Simulation” och därunder, ”Start. Om du vill ändra parametrar för simuleringen kan du under menyn ”Simulation” välja ”Parameters”. Du får då följande figur:



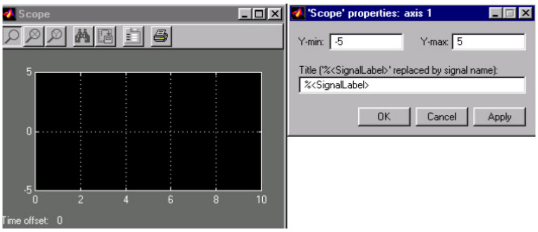
Start time: 0.0
Stop time: 10.0
Type: Variable-step
ode45 (Dormand-Prince)
Max step size: auto
Relative tolerance: 1e-3
Initial step size: auto
Absolute tolerance: 1e-6
Refine output
Refine factor: 1

Du kan välja start- och stopptid för simuleringen. Dessa bör väljas så att händelse förloppet syns på ett vettigt sätt i grafen (”Scope”). Du kan ju inte välja samma skala om du har frekvensen 1 kHz som om du har frekvensen 1 Hz.

Ibland måste du välja Max step size. Om du t.ex. kör med värden från 0-0.1s bör steglängden aldrig vara större än 0.001s. Ju fler punkter som ritas i figuren, desto bättre noggrannhet i svaret, men också längre simuleringstid.

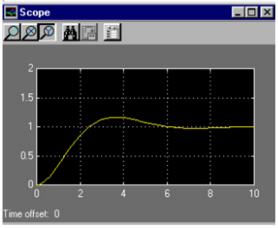
Om du dubbelklickar på ”Scope” i din figur får du upp grafen som vi

Du kanske får olämplig skala: Dubbelklicka då på "kikaren". Får du ändå inte en skala du är nöjd med kan du även ändra skalan manuellt: Klicka då med högertangenten (på musen) på en axel i figuren. Du får då upp rutan ”Axis Properties”:



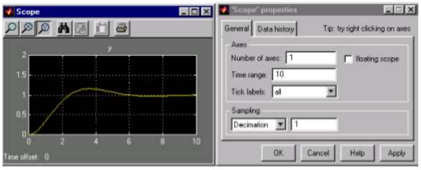
Y-min: -5
Y-max: 5
Title ('%<SignalLabel>' replaced by signal name): %<SignalLabel>

Där kan du ändra t.ex. Ymax, så att hela grafen syns:



För att ändra på parametrar för tidsaxeln kan du klicka på den lilla symbolen längst till höger på verktygsfältet:

Då får du upp den högra figuren nedan: ”Scope Properties ”



Number of axes: 1
☐ floating scope
Time range: 10
Tick labels: all
Decimation: 1

Observera att ”Time range” bör vara lika stor som den tid du valt för simuleringen.

I figuren kan du nu mäta t.ex. Hur stor översväng du har, vilken stigtid, resp inställningstid systemet har, samt vilket slutvärde stegsvaret har.

1.2 Uppgift 1

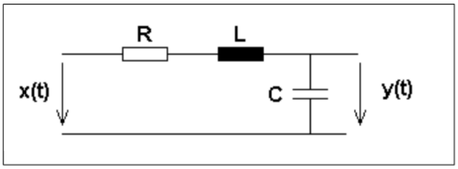
Låt $G(s) = \dfrac{3s+5}{s^2+2s+5}$

Beräkna tidsfunktionen (inverstransformen) av $\frac{1}{s} \cdot G(s)$

Simulera nu samma funktion, dvs låt G(s) vara den funktion du lägger in i blocket "transfer fcn"

Hur ändras stegsvaret (tidsfunktionen) om du ändrar nämnaren till $s^2 + 2s + 1$ resp. $s^2 + 2s + 0.25$? Gör beräkningarna för hand samt simulera stegsvaret i Simulink. Försök att, utifrån de beräkningar du gjort samt de bilder scope ger, dra slutsatser om hur kurvans utseende förändras med nämnarens koefficienter.

1.3 Uppgift 2



R= 100 Ω, L= 100 mH, C= 100 µF, $x(t) = \begin{cases} 1\text{V}, t \geq 0 \\ 0\text{V}, t < 0 \end{cases}$

Ställ upp uttrycket för $G(s) = \frac{Y(s)}{X(s)}$

Ledning: Impedanserna är för kondensatorn $\frac{1}{sC}$ respektive för spolen *sL*.

Fråga:

Hur ändras y(t) då C ändras från 100 µF till 10 µF? Varför? Försök att ge förklaringen både utifrån ett matematiskt resonemang, dels utifrån ett fysikaliskt.

1.4 Uppgift 3

Beräkna stegsvaret för kresten ovan, dvs *y(t)* då $x(t) = \begin{cases} 1\text{V}, t \geq 0 \\ 0\text{V}, t < 0 \end{cases}$ för några olika värden på komponenterna. Gör lämpligen beräkningarna för de värden på R, C resp. L som finns på labkortet som används i laborationen, dvs. R = 10Ω, 33Ω, 100Ω, C = 100μF, 330μF och L = 8.2mH

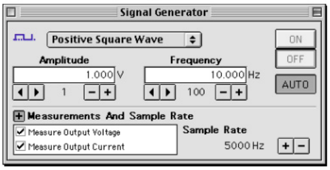
Ledning: Beräkna inverstransformen för $\frac{1}{s} \cdot G(s)$

Försök att identifiera koefficienterna a, b, c resp. d i $y(t) = a \cdot e^{bt} \sin(ct + d)$

2. Stegsvar hos RLC-krets studerat med DataStudio

2.1 Inställningar

Starta `DataStudio` på samma sätt som i tidigare laborationer. Om pulsbredden är tillräckligt stor i förhållande till kretsens tidskonstanter kan vi använda en fyrkantvåg för att erhålla ett steg. Lämpliga inställningar visas nedan. Observera den höga `Sample Rate`. Varför används hög `Sample Rate`?



Signal Generator

Positive Square Wave

Amplitude: 1.000 V

Frequency: 10.000 Hz

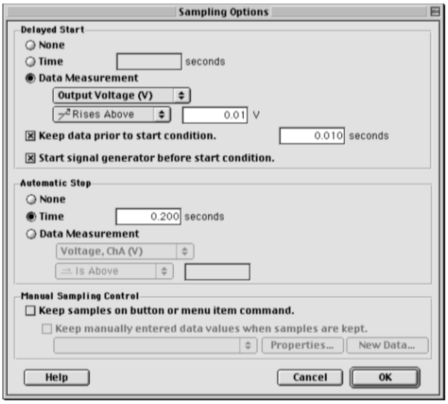
Measurements And Sample Rate

☑ Measure Output Voltage

☑ Measure Output Current

Sample Rate: 5000 Hz

Det är också lämpligt att ställa in start- och stoppvillkor enligt nedan:



Sampling Options

Delayed Start

○ None

○ Time seconds

● Data Measurement

Output Voltage (V)

Rises Above 0.01 V

☒ Keep data prior to start condition. 0.010 seconds

☒ Start signal generator before start condition.

Automatic Stop

○ None

● Time 0.200 seconds

○ Data Measurement

Voltage, ChA (V)

Is Above

Manual Sampling Control

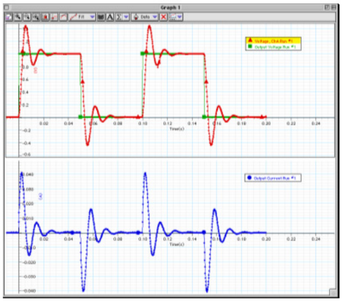
☐ Keep samples on button or menu item command.

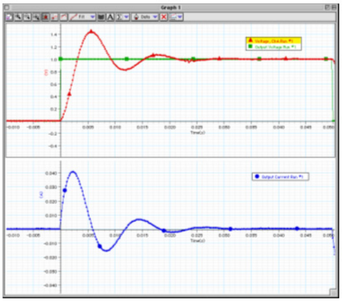
☐ Keep manually entered data values when samples are kept.

2.2 Första mätning

Vi är nu klara för mätning och det återstår att koppla upp kretsen fysiskt. Som krets används den färdiga RLC-krets som vi har utnyttjat tidigare. Vid den första mätningen utnyttjas C = 100 μF och som R utnyttjas spolens egen resistans (d v s inget separat R inkopplas) Anslut en spänningsgivare (`Voltage Sensor`) till kanal `A` för mätning av spänningen över ansluten kondensator och koppla utgångarna från `Output` med vanliga lab-sladdar över hela RLC kretsen.

Vi är nu klara för mätning. Starta mätning genom att klicka på knappen `Start` i DataStudio. Om allt fungerar har ni nu fått en graf liknande den nedan till vänster. Som alltid är det lämpligt att nu spara (`Save Activity`).





Denna figur kan nu skalas om för att få fram själva "stegsvaret". Denna skalning kan ske på olika sätt: Man kan dubbelklicka i figuren och få fram möjligheten att ställa in skalor på axlarna, man kan utnyttja zoom-verktyget eller man kan "peka" nära någon siffra på en axel och "dra".

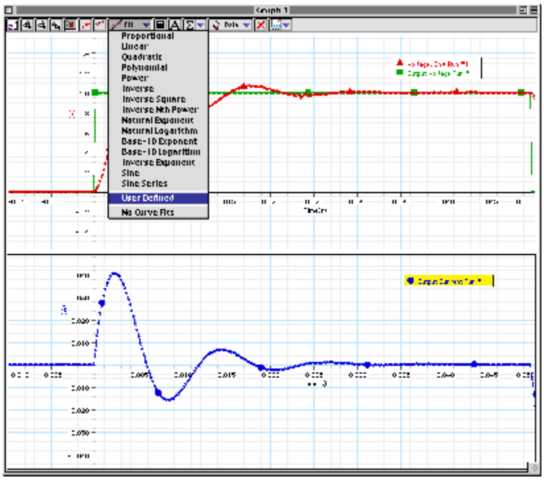
2.3 Ytterligare mätningar

Mätningarna upprepas med samma värde på L och C men med R = 10 Ω, 33 Ω respektive 100 Ω. (Observera punkten om bearbetning nedan. Ni avgör själva om ni gör bearbetningen efter varje mätning eller mäter först och bearbetar sedan.) Vilka skillnader observerar ni?

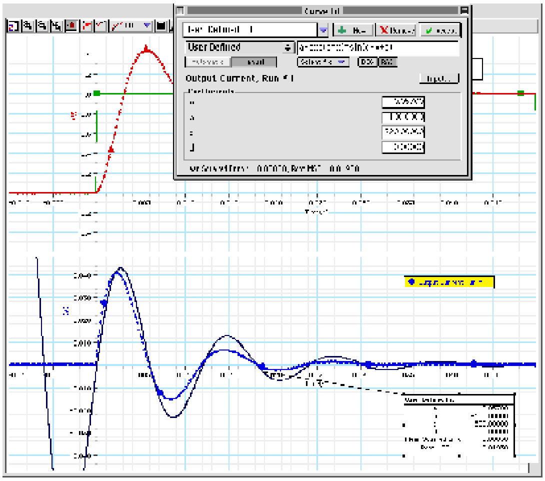
Genom att sätta in järnkärnan i spolen ungefär fördubblas dennas induktans. Gör detta och upprepa mätning med dels $R = R_{spole}$ respektive 10 Ω. Vad observeras? Slutligen tag ur järnkärnan och använd $R = R_{spole}$ men använd C = 330 μF.

2.4 Bearbetning

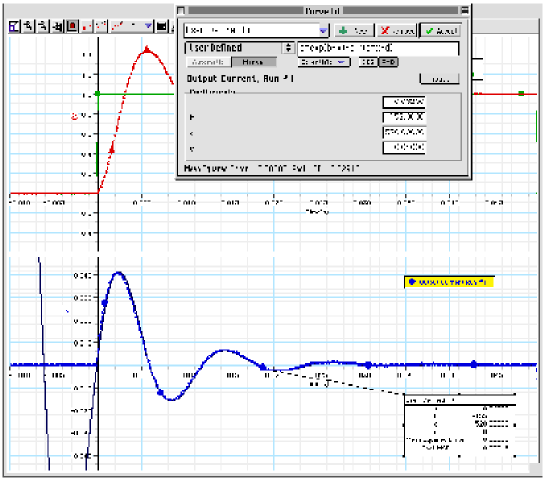
Mätning med datorinterface innebär att data finns lagrade och kan exporteras till Excel eller annat program för vidare behandling. DataStudio-programmet innehåller en möjlighet att göra en s k `Fit` (anpassning) till experimentella data. Nedan visas en anpassning av uppmätt ström genom kretsen till en dämpad sinus. Då denna inte fanns med bland de färdiga funktionerna har `Fit/User Definied` valts.


Graph 1
Fit
Proportional
Linear
Quadratic
Polynomial
Power
Inverse
Inverse Square
Inverse Nth Power
Natural Exponent
Natural Logarithm
Base-10 Exponent
Base-10 Logarithm
Inverse Exponent
Sine
Sine Series
User Defined
No Curve Fits
0.020
0.010
0.005
0.010
0.015
-0.010
-0.020
-0.030

Nedan visas inmatningen av en dämpad sinus i `User-Defined Fit`. Värdena ändras manuellt tills en så bra anpassning som möjligt erhålls. Vid anpassningen nedan är man inte riktigt framme. Prova att ändra de olika konstanterna för att få en känsla för vad de står för. Vad innebär ett stort eller litet värde?



Här har man fått så bra anpassning som är möjligt vid en manuell anpassning.



Ni skall göra anpassningar för den experimentellt uppmätta strömmen i(t) för mätningarna med L och C konstanta (8,2 mH respektive 100 μF) men med olika $R = R_{spole}$, R = 10 Ω, 33 Ω respektive 100 Ω. Utifrån de anpassningar ni får skall ni beräkna vilka värden på R, L och C detta motsvarar (Ledning: Lös uttrycket för strömmen med Laplace). Observera att beroende på vilket värde som R har så kommer lämplig funktion att anpassa till att vara olika.

3. Frivillig beräkningsuppgift

Lös diffekvationen $y''' + 3y'' + y' + Ky = K$ för lämpliga värden på K.

Låt t variera mellan 0 och 50.

För vilka K-värden är det intressant att lösa ekvationen?

a) Redovisa kurvor över y(t) för olika värden på K. (K ändras via kommandofönstret, t.ex. genom att sätta K=0:1:10)

b) För vilket värde på K blir integralen av $\left|1 - y(t)^2\right|$ minimal?

Användbara block ur Simulinkbiblioteket:

Integrator	ur Continous
Constant	ur Sources
Scope	ur Sinks
Gain	ur Math
Sum	ur Math
Abs	ur Math
Product	ur Math

4. Redovisning

Laborationen redovisas genom en s k fullständig rapport per grupp. Denna ska bl a innehålla en kortfattad beskrivning av försöket, figurer från simuleringar, mätningar och anpassningarna (behövs ej separat figur utan anpassning för de fall som en anpassning görs). Det skall framgå vilken funktion som ni har anpassat mot och vilka värden på R, L och C som anpassningen motsvarar. Skillnaderna mellan de olika resultaten skall beskrivas samt också förklaras utifrån teorin. Figurerna kan antingen bifogas från direkt utskrift från DataStudio eller genom att dessa har infogats i ett ordbehandlingsdokument.

12 References

Apelkrans, Mats, & Åbom, Carita. (2001). *OOS/UML : en objektorienterad systemutvecklingsmodell för processorienterad affärsutveckling*. Lund: Studentlitteratur.

Arnroth, Thomas. (2000). Vibrerande vägmarkeringar ger säkrare vägar. *Jönköpingsposten*, 23 Sept. 2000.

Baillie, Caroline, & Bernhard, Jonte. (2009). Educational research impacting engineering education. *European Journal of Engineering Education, 34*(4), 291-294.

Baillie, Caroline, Bowden, JohnA, & Meyer, Jan H. F. (2013). Threshold capabilities: threshold concepts and knowledge capability linked through variation theory. *Higher Education, 65*(2), 227-246.

Barnes, Douglas. (1976). *From communication to curriculum*. Harmondsworth.

Becu-Robinault, Karine, & Tiberghien, Andrée. (1998). Integrating Experiments into the Teaching of Energy. *International Journal of Science Education, 20*(1), 99-114.

Berner, Boel. (1999). *Perpetuum mobile?: teknikens utmaningar och historiens gång*. Lund: Arkiv.

Bernhard, Jonte. (2012). Learning through artifacts in engineering education. In N. M. Seel (Ed.), *Encyclopedia of the Sciences of Learning* (pp. 1983-1986). New York: Springer.

Bernhard, Jonte. (2013, Sept 16-20). *Is engineering education research engineering?* Paper presented at the SEFI annual conference, Leuven.

Bernhard, Jonte, & Carstensen, Anna-Karin. (2002, June 5-7). *Learning and teaching electrical circuit theory.* Paper presented at the PTEE 2002: Physics Teaching in Engineering Education, Leuven.

Bernhard, Jonte, Carstensen, Anna-Karin, & Holmberg, Margarita. (2010, September 19-22). *Investigating engineering students' learning – 'learning as the learning of a complex concept'.* Paper presented at the IGIP-SEFI 2010, Trnava.

Bernhard, Jonte, Carstensen, Anna-Karin, & Holmberg, Margarita. (2011). Analytical tools in engineering education research: The "learning a complex concept" model, threshold concepts and key concepts in understanding and designing for student learning. In W. Hernandez (Ed.), *Proceedings of Research in Engineering Education Symposium 2011* (pp. 51-60). Madrid: Universidad Politécnica de Madrid (UPM).

Bernhard, Jonte, Carstensen, Anna-Karin, & Holmberg, Margarita. (2013, Sept 16-20). *Phase as a key concept in physics and electrical engineering.* Paper presented at the SEFI annual conference, Leuven.

Booth, Shirley. (1992). *Learning to program: A phenomenographic perspective*. Gothenburg: Acta Universitatis Gothoburgensis.

Booth, Shirley. (2004). Engineering education and the pedagogy of awareness. In C. Baillie & I. Moore (Eds.), *Effective Learning and Teaching in Engineering* (pp. 9-23). New York: RoutledgeFalmer.

Borgmann, Albert. (1984/2003). Focal Things and Practices. In R. C. Scharff & V. Dusek (Eds.), *Philosophy of technology: the technological condition: an anthology* (pp. 293-314). Malden, MA: Blackwell Publishers.

Borrego, Maura, & Bernhard, Jonte. (2011). The Emergence of Engineering Education Research as an Internationally Connected Field of Inquiry. *Journal of Engineering Education, 100*(1), 14-47.

Bowden, John, & Marton, Ference. (1998). The University of Learning. Beyond Quality and Competence in Higher Education: Sterling, VA: Stylus Publishing.

Box, G. E. P., & Draper, N. R. (1987). *Empirical Model Building and Response Surfaces*. New York: John Wiley & Sons.

Brna, Paul, Baker, Michael, Stenning, Keith, & Tiberghien, Andrée (Eds.). (2002). *The role of communication in learning to model*. Mahwah, NJ: L. Erlbaum Associates.

Buty, Christian, Tiberghien, Andrée, & Le Marechal, Jean-Francois. (2004). Learning Hypotheses and an Associated Tool to Design and to Analyse Teaching-Learning Sequences. Special Issue. *International Journal of Science Education, 26*(5), 579-604.

Carstensen, Anna-Karin, & Bernhard, Jonte. (2002, June 5-7). *Bode plots not only a tool of engineers, but also a key to facilitate students learning in electrical and control engineering.* Paper presented at the PTEE 2002: Physics Teaching in Engineering Education, Leuven.

Carstensen, Anna-Karin, & Bernhard, Jonte. (2004, August 18-21). *Laplace transforms - too difficult to teach, learn and apply, or just matter of how to do it.* Paper presented at the EARLI sig#9 Conference, Gothenburg.

Carstensen, Anna-Karin, & Bernhard, Jonte. (2008). Threshold concepts and keys to the portal of understanding: Some examples from electrical engineering. In R. Land, E. Meyer & J. Smith (Eds.), *Threshold concepts within the disciplines* (pp. 143-154). Rotterdam: Sense Publishers.

Carstensen, Anna-Karin, & Bernhard, Jonte. (2009). Student Learning in an Electric Circuit Theory Course: Critical Aspects and Task Design. *European Journal of Engineering Education, 34*(4), 393-408.

Clark, Andy, & Chalmers, David. (1998). The extended mind. *Analysis, 58*(1), 7-19.

Cobb, Paul, Confrey, Jere, diSessa, Andrea, Lehrer, Richard, & Schauble, Leona. (2003). Design Experiments in Educational Research. *Educational Researcher, 32*(1), 9-13.

Cohen, Richard A., Eylon, B, & Ganiel, U. (1983). Potential difference and current in simple electric circuits: A study of students' concepts. *American Journal of Physics, 51*, 407-412.

Cope, Chris, & Byrne, Graeme. (2006). *Improving Teaching and Learning about Threshold Concepts: The Example of Confidence Intervals*. Paper presented at the Threshold Concepts within the disciplines, Glasgow, UK.

Davies, Peter, & Mangan, Jean. (2008). Embedding Threshold Concepts: from theory to pedagogical principles to learning activities. In R. Land, J. Meyer & J. Smith (Eds.), *Threshold Concepts within the Disciplines* (pp. 37-50). Rotterdam: Sense.

de Oliveira, José Manuel Nunes, & de Oliveira, João Pedro Estima. (2010, 19-22 September). *Important Problem Features For The Promotion of Conceptual Understanding in Introductory Electronics.* Paper presented at the IGIP-SEFI 2010, Trnava.

de Vries, Marc J. (2005). The Nature of Technological Knowledge: Philosophical Reflections and Educational Consequences. *International Journal of Technology and Design Education, 15*(2), 149-154.

Dewey, John. (1916). *Democracy and education: an introduction to the philosophy of education*. New York: Macmillan.

Duit, R, & von Rhöneck, C. (1997). *Learning and understanding key concepts of electricity* A. Tiberghien, E. L. Jossem & J. Borojas (Eds.), *Connecting Research in Physics Education with Teacher Education.* Retrieved Januari 7 2009 from http://www.physics.ohio-state.edu/~jossem/ICPE/C2.html

Eckerdal, Anna. (2012). Theory and practice in lab work – a complex interplay. Retrieved August 13 2013, from http://www.it.uu.se/research/group/upcerg_new/projects/T-PIPE/T-PIPE-Application-Attachment-A.pdf

Eggelston, John. (1994). What is design and technology education? *Teaching technology* (pp. 20-35). London: Routledge in association with the Open University.

Emanuelsson, Jonas. (2001). *En fråga om frågor : hur lärares frågor i klassrummet gör det möjligt att få reda på elevernas sätt att förstå det som undervisningen behandlar i matematik och naturvetenskap*. Göteborg: Acta Universitatis Gothoburgensis.

Entwistle, Noel. (2005). Enhancing teaching-learning environments in undergraduate courses in electronic engineering: an introduction to the ETL project. *International Journal of Electrical Engineering Education, 42*(1), 1-7.

Entwistle, Noel, Hamilton, Alister, Kelly, Robert, Nisbet, Jennifer, Chapman, Roy, Hayward, Gordon, & Gachagan, Tony. (2005). Teaching and learning analogue electronics in undergraduate courses: preliminary findings from the ETL project. *International Journal of Electrical Engineering Education, 42*(1), 8-20.

Entwistle, Noel, Nisbet, Jennifer, & Bromage, Adrian. (2005). ETL-Project: Subject Area Report for Electronic Engineering.

Evans, Alan, Martin, Kendall, & Poatsy, Mary Anne. (2006). *Technology in action*. Upper Saddle River, N.J.: Pearson Prentice Hall.

Flanagan, M. T., Taylor, P., & Meyer, J. H. F. (2010). Compounded Thresholds in Electrical Engineering. In J. H. F. Meyer, R. Land & C. Baillie (Eds.), *Threshold concepts and transformational learning*. Rotterdam: Sense Publishers.

Foley, Brian. (2012, 27-29 June). *Engineering Problem Solving: Uncovering a Threshold Experience and Triggering a Meta-Learning Response.* Paper presented at the Threshold Concepts Conference, Dublin.

Fraser, Duncan, & Linder, Cedric. (2009). Teaching in Higher Education through the Use of Variation: Examples from Distillation, Physics and Process Dynamics. *European Journal of Engineering Education, 34*(4), 369-381.

Fredlund, Tobias, Airey, John, & Linder, Cedric. (2012). Exploring the Role of Physics Representations: An Illustrative Example from Students Sharing Knowledge about Refraction. *European Journal of Physics, 33*(3), 657-666.

Garrison, Ervan G. (1991). *A history of engineering and technology: artful methods*. Boca Raton: CRC Press.

Gerlee, Philip, & Lundh, Torbjörn. (2012). *Vetenskapliga modeller : svarta lådor, röda atomer och vita lögner*. Lund: Studentlitteratur.

Gies, Frances, & Gies, Joseph. (1994). *Cathedral, forge, and waterwheel: technology and invention in the Middle Ages*. New York: HarperCollins Publishers.

González Sampayo, Margarita. (2006). *Engineering problem solving: The case of the Laplace transform as a difficulty in learning electric circuits and as a tool to solve real world problems.* Linköping: Linköping Studies in Science and Technology Dissertation No. 1038.

Haglund, Jesper. (2012). *Analogical reasoning in science education: connections to semantics and scientific modelling in thermodynamics*. Norrköping: Department of Social and Welfare Studies, Linköping University.

Hansson, Staffan. (2002). *Den skapande människan: om människan och tekniken under 5000 år*. Lund: Studentlitteratur.

Harlow, A., Scott, J., Peter, M., & Cowie, B. (2011). 'Getting stuck' in analogue electronics: threshold concepts as an explanatory model. *European Journal of Engineering Education, 36*(5), 435-447.

Heidegger, Martin. (1954/2003). The Question Concerning Technology. In R. C. Scharff & V. Dusek (Eds.), *Philosophy of technology: the technological condition: an anthology* (pp. 252-264). Malden, MA: Blackwell Publishers.

Hestenes, David. (1987). Toward a modeling theory of physics instruction. *American Journal of Physics, 55*(5), 440-454.

Hestenes, David. (1992). Modeling games in the Newtonian World. *American Journal of Physics, 60*(8), 732-748.

Hickman, Larry A. (1990). *John Dewey's pragmatic technology*. Bloomington: Indiana Univ. Press.

Holmqvist, Mona, Gustavsson, Laila, & Wernberg, Anna. (2007). Generative learning: learning beyond the learning situation. *Educational Action Research, 15*(2), 181-208.

Hussain, Noor Hamizah, Latiff, Liza Abdul, & Yahaya, Nazli. (2012). Alternative conception about open and short crcuit concepts. *Procedia - Social and Behavioral Sciences, 56*(0), 466-473.

Hussain, Noor Hamizah, Salim, Kamilah Radin, Haron, Habibah Norehan, Ali, Rosmah, & Hussain, Habsah. (2013, July 4-6). *Students's alternative conception in basic electric circuit.* Paper presented at the Research in Engineering Education Symposium, Kuala Lumpur.

Hutchins, Edwin. (1995). *Cognition in the Wild*. Cambridge, MA: MIT Press.

Ihde, Don. (1979/2003). Heiddegger's Philosophy of Technology. In R. C. Scharff & V. Dusek (Eds.), *Philosophy of technology: the technological condition: an anthology* (pp. 277-292). Malden, MA: Blackwell Publishers.

Ihde, Don. (1986). *Experimental Phenomenology: An Introduction*. Albany: State University of New York Press.

Ihde, Don. (1991). *Instrumental realism: The interface between philosophy of science and philosophy of technology*. Bloomington: Indiana University Press.

Ihde, Don. (1993). *Postphenomenology: Essays in the Postmodern Context*. Evanston: Northwestern University Press.

Ihde, Don. (2006). Forty Years in the Wilderness. In E. Selinger (Ed.), *Postphenomenomenology: A Critical Companion to Ihde* (pp. 267-290). Albany: State University of New York Press.

Ihde, Don. (2009). *Postphenomenology and technoscience: The Peking university lectures*. Albany: State University of New York Press.

Indo-European roots. (2003). Retrieved October 17 2003, from http://www.bartleby.com/61/roots/IE143.html

Ingelstam, Lars. (2002). *System : att tänka över samhälle och teknik*. Eskilstuna: Statens energimyndighet.

Kautz, Christian. (2008). *Probing Student Understanding of Basic Concepts in Introductory Electrical Engineering Courses.* Paper presented at the SEFI 2008, Aalborg.

Kautz, Christian. (2009). *Tutorien zur Elektrotechnik*. München: Pearson Studium.

Kautz, Christian. (2011a, 27-30 September). *Development of instructional materials to address student difficulties in introductory electrical engineering.* Paper presented at the WEE2011, Lisbon.

Kautz, Christian. (2011b). *Student understanding of modeling aspects in introductory circuit analysis.* Paper presented at the Research in Engineering Education Symposium, Madrid.

Knuuttila, Tarja. (2011). Modelling and representing: An artefactual approach to model-based representation. *Studies in History and Philosophy of Science Part A, 42*(2), 262-271.

Koponen, IsmoT, & Huttunen, Laura. (2012). Concept Development in Learning Physics: The Case of Electric Current and Voltage Revisited. *Science & Education*.

Lamont, L. A., Chaar, L., & Toms, C. (2010). Using interactive problem-solving techniques to enhance control systems education for non English-speakers. *European Journal of Engineering Education, 35*(1), 99-108.

Land, Ray, Cousin, Glynis, Meyer, Jan H. F., & Davies, Peter. (2005). Threshold concepts and troublesome knowledge (3): implications for course design and evaluation. In C. Rust (Ed.), *Improving Student Learning - diversity and inclusivity, Proceedings of the 12th Improving Student Learning Conference* (pp. 53-64): Oxford: Oxford Centre for Staff and Learning Development (OCSLD).

Land, Ray, Meyer, Jan H. F., & Smith, Jan (Eds.). (2008). *Threshold concepts within the disciplines*. Rotterdam: Sense.

Laudan, Rachel. (1984). *The nature of technological knowledge : are models of scientific change relevant?* Dordrecht: Reidel.

Lederman, Judith, & Lederman, Norman (n. d.). Tube Activity. Retrieved July 23 2013, from http://msed.iit.edu/projectican/tube.html

Lindqvist, Svante. (1989). Trä, vatten och muskelkraft: 1720-1815 *Svensk Teknikhistoria*.

Ljung, Lennart, & Glad, Torkel. (1994). *Modeling of dynamic systems*. Englewood Cliffs: Prentice Hall.

Malmberg, Roger. (2007). *Analog circuit topology development : practice methods for technology and teaching based on comprehensible transistor models*. Göteborg: Chalmers University of Technology.

Marton, Ference, & Booth, Shirley. (1997). *Learning and awareness*. Mahwah, N.J.: Erlbaum.

Marton, Ference, & Morris, Paul. (2002a). What Matters? In F. Marton & P. Morris (Eds.), *What Matters? Discovering critical conditions of classroom learning* (pp. 75-92). Göteborg: Acta Universitatis Gothoburgensis.

Marton, Ference, & Morris, Paul (Eds.). (2002b). *What matters? Discovering critical conditions of classroom learning*. Göteborg: Acta Universitatis Gothoburgensis.

Marton, Ference, Runesson, Ulla, & Tsui, Amy B M. (2004). The Space of Learning. In F. Marton & A. B. M. Tsui (Eds.), *Classroom discourse and the space of learning* (pp. 3-42). Mahwaw: Lawrence Erlbaum.

Marton, Ference, & Säljö, Roger. (2005). Approaches to Learning. In F. Marton, D. Hounsell & EntwistleNoel (Eds.), *The Experience of Learning: Implications for teaching and studying in higher education* (3rd Internet Edition ed., pp. 39-58): Edinburgh: University of Edinburgh, Centre for Teaching, Learning and Assessment.

Marton, Ference, & Tsui, Amy B M (Eds.). (2004). *Classroom discourse and the space of learning*. Mahwaw: Lawrence Erlbaum.

McClellan, James E., & Dorn, Harold. (1999). *Science and technology in world history : an introduction*. Baltimore, Md.: Johns Hopkins Univ. Press.

McDermott, Lillian C, & Shaffer, Peter S. (1992). Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding. *American Journal of Physics, 60*(11), 994-1003.

Meyer, Jan H. F. , & Land, Ray. (2003). Threshold concepts and troublesome knowledge: linkages to ways of thinking and practising. In C. Rust (Ed.), *Improving Student Learning - Theory and Practice Ten Years On* (pp. 412-424.): Oxford: Oxford Centre for Staff and Learning Development (OCSLD).

Meyer, Jan H. F., & Land, Ray. (2006). *Overcoming barriers to student understanding : threshold concepts and troublesome knowledge*. Abingdon, Oxon ;: Routledge.

Meyer, Jan H. F., Land, Ray , & Davies, Peter. (2008). Threshold concepts and troublesome knowledge (4): Issues of variation and variability. In R. Land, J. Meyer & J. Smith (Eds.), *Threshold Concepts within the Disciplines* (pp. 59-74). Rotterdam: Sense.

Mitcham, Carl. (1994). *Thinking through technology: the path between engineering and philosophy*. Chicago: Univ. of Chicago Press.

Molander, Bengt. (1993). *Kunskap i handling*. Göteborg: Daidalos.

Nilsson, James William, & Riedel, Susan A. (2001). *Electric circuits*. Upper Saddle River: Prentice-Hall.

Periago, M Cristina, & Bohigas, Xavier. (2005). A study of second-year engineering students' alternative conceptions about electric potential, current intensity and Ohm's law. *European Journal of Engineering Education, 30*(1), 71-80.

Perkins, David. (2006). Constructivism and troublesome knowledge. In J. H. F. Meyer & R. Land (Eds.), *Overcoming barriers to student understanding : threshold concepts and troublesome knowledge* (pp. 33-47). Abingdon, Oxon ;: Routledge.

Polanyi, Michael. (1967). *The tacit dimension*. Garden City, N.Y.: Doubleday.

Psillos, Dimitris, & Niedderer, Hans. (2002). *Teaching and learning in the science laboratory*. Dordrecht: Kluwer Academic Publishers.

Redfors, Andreas, & Ryder, Jim. (2001). University Physics Students' Use of Models in Explanations of Phenomena Involving Interaction between Metals and Electromagnetic Radiation. *International Journal of Science Education, 23*(12), 1283-1301.

Renström, Lena. (1988). *Conceptions of matter: a phenomenographic approach*. Göteborg: Acta Universitatis Gothoburgensis.

Ropohl, Gunter. (1997). Knowledge Types in Technology. *International Journal of Technology and Design Education, 7*(1-2), 65-72.

Roth, Wolff-Michael. (1995). *Authentic school science: Knowing and learning in open-inquiry science laboratories*. Dordrecht: Kluwer.

Runesson, Ulla, & Marton, Ference. (2002). The object of learning and the space variation. In F. Marton & P. Morris (Eds.), *What matters? Discovering critical conditions of classroom learning* (pp. 19-38). Göteborg: Acta Universitatis Gothoburgensis.

Ryegård, Åsa. (2004). *Interaktion mellan teoretiskt och praktiskt lärande: en studie i elektronikundervisning på högskolenivå*. Västerås: Mälardalen University.

Ryegård, Åsa. (2005). *Laborationer i elektronik*. Unpublished document. Västerås: Mälardalen University.

Schön, Donald A. (1983). *The reflective practitioner : how professionals think in action*. New York: Basic Books.

Sensevy, Gérard, Tiberghien, Andrée, Santini, Jerome, Laube, Sylvain, & Griggs, Peter. (2008). An Epistemological Approach to Modeling: Cases Studies and Implications for Science Teaching. *Science Education, 92*(3), 424-446.

Sjøberg, Svein. (2000). *Naturvetenskap som allmänbildning: en kritisk ämnesdidaktik* (A. Claesdotter, Trans.). Lund: Studentlitteratur.

Skogh, Inga-Britt. (2001). *Teknikens värld - flickors värld : en studie av yngre flickors möte med teknik i hem och skola*. Stockholm: HLS förl.

Skolimowski, Henryk. (1968). *On the concept of truth in science and in technology.* Paper presented at the XIV International Congress of Philosophy, Vienna.

Streveler, Ruth, Geist, Monica, Ammerman, Ravel, Sulzbach, Candace, Miller, Ronald, & Olds, Barbara. (2006). *Identifying and investigating difficult concepts in engineering mechanics and electric circuits.* Paper presented at the 113th Annual ASEE Conference, Chicago, IL.

Strömdahl, Helge. (1996). On mole and amount of substance. Göteborg: Acta Universitatis Gothoburgensis.

Thomas, Roland E., Rosa, Albert J., & Toussaint, Gregory J. (2012). *The Analysis and Design of Linear Circuits*. New York: John Wiley & Sons.

Thuné, Michael, & Eckerdal, Anna. (2009). Variation Theory Applied to Students' Conceptions of Computer Programming. *European Journal of Engineering Education, 34*(4), 339-347.

Tiberghien, Andrée. (1998). Labwork activity and learning physics - an approach based on modeling. In J. Leach & A. Paulsen (Eds.), *Practical work in science education* (pp. 176-194). Fredriksberg: Roskilde University Press.

Tiberghien, Andrée. (1998). *Analysis of Teaching and Learning: How differentiating and Relating Them*. Paper presented at the ESERA Summerschool 1998.

Tiberghien, Andrée. (2000). Designing teaching situations in the secondary school. In R. Millar, J. T. Leach & J. Osborne (Eds.), *Improving science education: the contribution of research* (pp. 27-47). Buckingham: Open University Press.

Tiberghien, Andrée, Veillard, Laurent, Le Marechal, Jean-Francois, Buty, Christian, & Millar, Robin. (2001). An Analysis of Labwork Tasks Used in Science Teaching at Upper Secondary School and University Levels in Several European Countries. *Science Education, 85*(5), 483-508.

Tiberghien, Andrée, Vince, Jacques, & Gaidioz, Pierre. (2009). Design-Based Research: Case of a Teaching Sequence on Mechanics. *International Journal of Science Education, 31*(17), 2275-2314.

Wickman, Per-Olof. (2004). The Practical Epistemologies of the Classroom: A Study of Laboratory Work. *Science Education, 88*(3), 325-344.

Wickman, Per-Olof, & Östman, Leif. (2002). Learning as Discourse Change: A Sociocultural Mechanism. *Science Education, 86*(5), 601-623.

Williams, John. (1996). Philosophy of technology education. In J. Williams & A. Williams (Eds.), *Technology education for teachers* (pp. 27-62). South Melbourne: Macmillan Education Australia.

Vince, Jacques, & Tiberghien, Andrée. (2002). Modelling in Teaching and Learning Elementary Physics. In P. Brna, M. Baker, K. Stenning & A. Tiberghien (Eds.), *The Role of Communication in Learning to Model* (pp. 49-68). Mahwah, NJ: Lawrence Erlbaum.

Vincenti, Walter Guido. (1990). *What engineers know and how they know it*. Baltimore: Johns Hopkins Univ. Press.

Wittgenstein, Ludwig. (1968). *Philosophical investigations: Philosophische Untersuchungen*. Oxford.

Studies in Science and Technology Education

ISSN 1652-5051
FontD

1. Margareta Enghag (2004): MINIPROJECTS AND CONTEXT RICH PROBLEMS – Case studies with qualitative analysis of motivation, learner ownership and competence in small group work in physics. (licentiate thesis) Linköping University
2. Carl-Johan Rundgren (2006): Meaning-Making in Molecular Life Science Education – upper secondary school students' interpretation of visualizations of proteins. (licentiate thesis) Linköping University
3. Michal Drechsler (2005): Textbooks', teachers', and students´ understanding of models used to explain acid-base reactions. ISSN: 1403-8099, ISBN: 91-85335-40-1. (licentiate thesis) Karlstad University
4. Margareta Enghag (2007): Two dimensions of Student Ownership of Learning during Small-Group Work with Miniprojects and context rich Problems in Physics. ISSN: 1651-4238, ISBN: 91-85485-31-4. (Doctoral Dissertation) Mälardalen University
5. Maria Åström (2007): Integrated and Subject-specific. An empirical exploration of Science education in Swedish compulsory schools. (Licentiate thesis) Linköping university
6. Ola Magntorn (2007): Reading Nature: developing ecological literacy through teaching. (Doctoral Dissertation) Linköping University
7. Maria Andreé (2007): Den levda läroplanen. En studie av naturorienterande undervisningspraktiker i grundskolan. ISSN: 1400-478X, HLS Förlag: ISBN 978-91-7656-632-9 (Doctoral Dissertation, LHS)
8. Mattias Lundin (2007): Students' participation in the realization of school science activities.(Doctoral Dissertation) Linköping University
9. Michal Drechsler (2007): Models in chemistry education. A study of teaching and learning acids and bases in Swedish upper secondary schools ISBN 978-91-7063-112-2 (Doctoral Dissertation) Karlstad University
10. Proceedings from FontD Vadstena-meeting, April 2006.
11. Eva Blomdahl (2007): Teknik i skolan. En studie av teknikundervisning för yngre skolbarn. ISSN: 1400-478X, HLS Förlag: ISBN 978-91-7656-635-0 (Doctoral Dissertation, LHS)
12. Iann Lundegård (2007): På väg mot pluralism. Elever i situerade samtal kring hållbar utveckling. ISSN:1400-478X, HLS Förlag: ISBN 978-91-7656-642-8 (Doctoral Dissertation, LHS)
13. Lena Hansson (2007): ”Enligt fysiken eller enligt mig själv?” – Gymnasieelever, fysiken och grundantaganden om världen. (Doctoral Dissertation) Linköping University.

Studies in Science and Technology Education
ISSN 1652-5051
FontD

14. Christel Persson (2008): Sfärernas symfoni i förändring? Lärande i miljö för hållbar utveckling med naturvetenskaplig utgångspunkt. En longitudinell studie i grundskolans tidigare årskurser. (Doctoral Dissertation) Linköping University
15. Eva Davidsson (2008): Different Images of Science – a study of how science is constituted in exhibitions. ISBN: 978-91-977100-1-5 (Doctoral Dissertation) Malmö University
16. Magnus Hultén (2008): Naturens kanon. Formering och förändring av innehållet i folkskolans och grundskolans naturvetenskap 1842-2007. ISBN: 978-91-7155-612-7 (Doctoral Dissertation) Stockholm University
17. Lars-Erik Björklund (2008): Från Novis till Expert: Förtrogenhetskunskap i kognitiv och didaktisk belysning. (Doctoral Dissertation) Linköping University.
18. Anders Jönsson (2008): Educative assessment for/of teacher competency. A study of assessment and learning in the "Interactive examination" for student teachers. ISBN: 978-91-977100-3-9 (Doctoral Dissertation) Malmö University
19. Pernilla Nilsson (2008): Learning to teach and teaching to learn - primary science student teachers' complex journey from learners to teachers. (Doctoral Dissertation) Linköping University
20. Carl-Johan Rundgren (2008): VISUAL THINKING, VISUAL SPEECH - a Semiotic Perspective on Meaning-Making in Molecular Life Science. (Doctoral Dissertation) Linköping University
21. Per Sund (2008): Att urskilja selektiva traditioner i miljöundervisningens socialisationsinnehåll – implikationer för undervisning för hållbar utveckling. ISBN: 978-91-85485-88-8 (Doctoral Dissertation) Mälardalen University
22. Susanne Engström (2008): Fysiken spelar roll! I undervisning om hållbara energisystem - fokus på gymnasiekursen Fysik A. ISBN: 978-91-85485-96-3 (Licentiate thesis) Mälardalen University
23. Britt Jakobsson (2008): Learning science through aesthetic experience in elementary school science. Aesthetic judgement, metaphor and art. ISBN: 978-91-7155-654-7. (Doctoral Dissertation) Stockholm university
24. Gunilla Gunnarsson (2008): Den laborativa klassrumsverksamhetens interaktioner - En studie om vilket meningsskapande år 7-elever kan erbjudas i möten med den laborativa verksamhetens instruktioner, artefakter och språk inom elementär ellära, samt om lärares didaktiska handlingsmönster i dessa möten. (Doctoral Dissertation) Linköping University
25. Pernilla Granklint Enochson (2008): Elevernas föreställningar om kroppens organ och kroppens hälsa utifrån ett skolsammanhang. (Licentiate thesis) Linköping University
26. Maria Åström (2008): Defining Integrated Science Education and putting it to test (Doctoral Dissertation) Linköping University
27. Niklas Gericke (2009): Science versus School-science. Multiple models in genetics – The depiction of gene function in upper secondary textbooks and its influence on students' understanding. ISBN 978-91-7063-205-1 (Doctoral Dissertation) Karlstad University

Studies in Science and Technology Education

ISSN 1652-5051

28. Per Högström (2009): Laborativt arbete i grundskolans senare år - lärares mål och hur de implementeras. ISBN 978-91-7264-755-8 (Doctoral Dissertation) Umeå University
29. Annette Johnsson (2009): Dialogues on the Net. Power structures in asynchronous discussions in the context of a web based teacher training course. ISBN 978-91-977100-9-1 (Doctoral Dissertation) Malmö University
30. Elisabet M. Nilsson (2010): Simulated ”real” worlds: Actions mediated through computer game play in science education. ISBN 978-91-86295-02-8 (Doctoral Dissertation) Malmö University
31. Lise-Lotte Österlund (2010): Redox models in chemistry: A depiction of the conceptions held by upper secondary school students of redox reactions. ISBN 978-91-7459-053-1 (Doctoral Dissertation) Umeå University
32. Claes Klasander (2010): Talet om tekniska system – förväntningar, traditioner och skolverkligheter. ISBN 978-91-7393-332-2 (Doctoral Dissertation) Linköping University
33. Maria Svensson (2011): Att urskilja tekniska system – didaktiska dimensioner i grundskolan. ISBN 978-91-7393-250-9 (Doctoral Dissertation) Linköping University
34. Nina Christenson (2011): Knowledge, Value and Personal experience – Upper secondary students' use of supporting reasons when arguing socioscientific issues. ISBN 978-91-7063-340-9 (Licentiate thesis) Karlstad University
35. Tor Nilsson (2011): Kemistudenters föreställningar om entalpi och relaterade begrepp. ISBN 978-91-7485-002-4 (Doctoral Dissertation) Mälardalen University
36. Kristina Andersson (2011): Lärare för förändring – att synliggöra och utmana föreställningar om naturvetenskap och genus. ISBN 978-91-7393-222-6 (Doctoral Dissertation) Linköping University
37. Peter Frejd (2011): Mathematical modelling in upper secondary school in Sweden An exploratory study. ISBN: 978-91-7393-223-3 (Licentiate thesis) Linköping University
38. Daniel Dufåker (2011): Spectroscopy studies of few particle effects in pyramidal quantum dots. ISBN 978-91-7393-179-3 (Licentiate thesis) Linköping University
39. Auli Arvola Orlander (2011): Med kroppen som insats: Diskursiva spänningsfält i biologiundervisningen på högstadiet. ISBN 978-91-7447-258-5 (Doctoral Dissertation) Stockholm University
40. Karin Stolpe (2011): Att uppmärksamma det väsentliga. Lärares ämnesdidaktiska förmågor ur ett interaktionskognitivt perspektiv. ISBN 978-91-7393-169-4 (Doctoral Dissertation) Linköping University
41. Anna-Karin Westman (2011) Samtal om begreppskartor – en väg till ökad förståelse. ISBN 978-91-86694-43-2 (Licentiate thesis) Mid Sweden University
42. Susanne Engström (2011) Att vördsamt värdesätta eller tryggt trotsa. Gymnasiefysiken, undervisningstraditioner och fysiklärares olika strategier för energiundervisning. ISBN 978-91-7485-011-6 (Doctoral Dissertation) Mälardalen University
43. Lena Adolfsson (2011) Attityder till naturvetenskap. Förändringar av flickors och pojkars attityder till biologi, fysik och kemi 1995 till 2007. ISBN 978-91-7459-233-7 (Licentiate thesis) Umeå University

Studies in Science and Technology Education

ISSN 1652-5051

44. Anna Lundberg (2011) Proportionalitetsbegreppet i den svenska gymnasiematematiken – en studie om läromedel och nationella prov. ISBN 978-91-7393-132-8 (Licentiate thesis) Linköping University
45. Sanela Mehanovic (2011) The potential and challenges of the use of dynamic software in upper secondary Mathematics. Students' and teachers' work with integrals in GeoGebra based environments. ISBN 978-91-7393-127-4 (Licentiate thesis) Linköping University
46. Semir Becevic (2011) Klassrumsbedömning i matematik på gymnasieskolans nivå. ISBN 978-91-7393-091-8 (Licentiate thesis) Linköping University
47. Veronica Flodin (2011) Epistemisk drift - genbegreppets variationer i några av forskningens och undervisningens texter i biologi. ISBN 978-91-9795-161-6 (Licentiate thesis) Stockholm University
48. Carola Borg (2011) Utbildning för hållbar utveckling ur ett lärarperspektiv – Ämnesbundna skillnader i gymnasieskolan. ISBN 978-91-7063-377-5 (Licentiate thesis) Karlstad University
49. Mats Lundström (2011) Decision-making in health issues: Teenagers' use of science and other discourses. ISBN 978-91-86295-15-8 (Doctoral Dissertation) Malmö University
50. Magnus Oscarsson (2012) Viktigt, men inget för mig. Ungdomars identitetsbygge och attityd till naturvetenskap. ISBN: 978-91-7519-988-7 (Doctoral Dissertation) Linköping University
51. Pernilla Granklint Enochson (2012) Om organisation och funktion av människokroppens organsystem – analys av elevsvar från Sverige och Sydafrika. ISBN 978-91-7519-960-3 (Doctoral Dissertation) Linköping University
52. Mari Stadig Degerman (2012) Att hantera cellmetabolismens komplexitet – Meningsskapande genom visualisering och metaforer. ISBN 978-01-7519-954-2 (Doctoral Dissertation) Linköping University
53. Anna-Lena Göransson (2012) The Alzheimer Aβ peptide: Identification of Properties Distinctive for Toxic Prefibrillar Species. ISBN 978-91-7519-930-6 (Licentiate thesis) Linköping University
54. Madelen Bodin (2012) Computational problem solving in university physics education - Students' beliefs, knowledge, and motivation. ISBN 978-91-7459-398-3 (Doctoral Dissertation) Umeå University
55. Lena Aretorn (2012) Mathematics in the Swedish Upper Secondary School Electricity Program: A study of teacher knowledge. ISBN 978-91-7459-429-4 (Licentiate thesis) Umeå University
56. Anders Jidesjö (2012) En problematisering av ungdomars intresse för naturvetenskap och teknik i skola och samhälle – Innehåll, medierna och utbildningens funktion. ISBN 978-91-7519-873-6 (Doctoral Dissertation) Linköping University
57. Thomas Lundblad (2012) Simulerad verklighet i gymnasieskolans fysik: en designstudie om en augmented reality simulering med socio-naturvetenskapligt innehåll. ISBN 978-91-7519-854-5 (Licentiate thesis) Linköping University
58. Annie-Maj Johansson (2012) Undersökande arbetssätt i NO-undervisningen i grundskolans tidigare årskurser. ISBN 978-91-7447-552-4 (Doctoral Dissertation) Stockholm University

Studies in Science and Technology Education

ISSN 1652-5051

FontD

59. Anna Jobér (2012) Social Class in Science Class. ISBN 978-91-86295-31-8 (Doctoral Dissertation) Malmö University
60. Jesper Haglund (2012) Analogical reasoning in science education – connections to semantics and scientific modeling in thermodynamics. ISBN 978-91-7519-773-9 (Doctoral Dissertation) Linköping University
61. Fredrik Jeppsson (2012) Adopting a cognitive semantic approach to understand thermodynamics within science education. ISBN 978-91-7519-765-4 (Doctoral Dissertation) Linköping University
62. Maria Petersson (2012) Lärares beskrivningar av evolution som undervisningsinnehåll i biologi på gymnasiet.ISBN 978-91-7063-453-6 (Doctoral Dissertation) Karlstad University
63. Henrik Carlsson (2012) Undervisningsform, klassrumsnormer och matematiska förmågor. En studie av ett lokalt undervisningsförsök för elever med intresse och fallenhet för matematik. ISBN 978-91-86983-89-5 (Licentiate thesis) Linnaeus University)
64. Anna Bergqvist (2012) Models of Chemical Bonding. Representations Used in School Textbooks and by Teachers and their Relation to Students' Understanding. ISBN 978-91-7063-463-5 (Licentiate thesis) Karlstad University
65. Nina Kilbrink (2013) Lära för framtiden: Transfer i teknisk yrkesutbildning. ISBN 978-91-7063-478-9 (Doctoral Dissertation) Karlstad University
66. Caroline Larsson (2013) Experiencing Molecular Processes. The Role of Representations for Students' Conceptual Understanding. ISBN 978-91-7519-607-7 (Doctoral Dissertation) Linköping University
67. Anna-Karin Carstensen (2013) Connect – Modelling Learning to Facilitate Linking Models and the Real World through Labwork in Electric Circuit Courses for Engineering Students ISBN 978-91-7519-562-9 (Doctoral Dissertation) Linköping University