Department of Radio Science and Engineering

Engineering students' proficiency in electromagnetics

Johanna Leppävirta

Aalto University

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ENGINEERING STUDENTS' PROFICIENCY IN ELECTROMAGNETICS
Role of procedural and conceptual knowledge, and mathematics anxiety in learning of electromagnetics

Johanna Leppävirta

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Abstract

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Abstract

Mathematical proficiency is an important predictor of engineering success. However, the change of the demographics of engineering students has led to larger percentage of students with weak mathematics skills. Furthermore, electromagnetics courses are perceived as abstract and irrelevant. Students struggle with required mathematics and have been shown to have motivational difficulties when studying the subject.

This thesis examines engineering students′ conceptual and procedural knowledge, as well as mathematics anxiety that all relate to proficiency in electromagnetics. Students' conceptual knowledge is measured with the Conceptual Survey of Electricity and Magnetism (CSEM). Procedural knowledge is assessed from students' performance in complex problem exercises and in the final exam. Mathematics anxiety is evaluated with the Electromagnetics Mathematics Anxiety Rating Scale (EMARS). The data (N=133) are collected from an undergraduate static field theory course at Helsinki University of Technology, Espoo, Finland. The data are analyzed using descriptive statistics, correlation, factor analysis, analysis of variance (ANOVA), linear regression, and Fisher's exact test.

The results show that there is a relationship between procedural and conceptual knowledge in the context of electromagnetics. The findings suggest that in the context of electromagnetics, a basic conceptual knowledge is a necessary but not a sufficient condition for acquiring procedural knowledge. The prior conceptual knowledge predicts success in the final exam, but developing students' procedural skill with complex problem exercises during the course does not significantly enhance students' conceptual knowledge. The study shows that prior to instruction, 18% of students have a consistent or partially consistent alternative model of Newton's third law principle. This model impacts the performance of students. The results show also that 16% of engineering students experience high mathematics anxiety. Anxiety is found to be impacting students' procedural performance but not conceptual. The findings suggest that there is clearly a need to broaden the view of what types of knowledge are valued and assessed in engineering courses.

Keywords conceptual and procedural knowledge; electromagnetics; engineering education; mathematics anxiety

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Tekijä
Johanna Leppävirta

Väitöskirjan nimi
TEKNILLISTIETEELLISEN ALAN OPISKELIJOIDEN MATEMAATTINEN KYVYKKYYS SÄHKÖMAGNETIIKAN OPISKELUSSA
Proseduraalisen ja käsitteellisen tiedon ja matematiikka-ahdistuksen vaikutukset oppimiseen

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Tiivistelmä

Matemaattiset kyvyt vaikuttavat keskeisesti siihen, miten opiskelijat suoriutuvat teknillistieteellisistä opinnoistaan. Muutokset opiskelija-aineksessa ovat viime vuosina johtaneet kuitenkin siihen, että matemaattisesti heikompien opiskelijoiden osuus on kasvanut. Tässä väitöskirjassa tutkittiin sähkö- ja tietoliikennetekniikan diplomi-insinööriksi opiskelevien matemaattisen kyvykkyyden kehittymistä sähkömagnetiikan opiskelussa.Työssä mitattiin opiskelijoiden käsitteellistä ja proseduraalista ymmärrystä sekä matematiikka-ahdistusta, jotka kaikki osaltaan vaikuttavat matemaattiseen kyvykkyyteen. Opiskelijoiden käsitteellistä tietoa mitattiin 'Conceptual Survey of Electricity and Magnetism' (CSEM) –mittarilla. Proseduraalista tietoa mitattiin opiskelijoiden menestymisellä kompleksisissa ongelmanratkaisutehtävissä ja lopputentissä. Matematiikka-ahdistusta mitatiin kyseistä tutkimusta varten kehitetyllä 'Electromagnetics Mathematics Anxiety Rating Scale' (EMARS) –mittarilla. Aineisto (N=133) kerättiin Staattinen kenttäteoria -peruskurssilla Teknillisessä korkeakoulussa. Analysointimenetelminä käytettiin kuvailevia tilastollisia menetelmiä, korrelaatiokerrointa, faktorianalyysiä, varianssianalyysiä (ANOVA), regressioanalyysiä sekä Fisherin testiä.

Tutkimuksessa käsitteellinen ja proseduraalinen tieto olivat yhteydessä toisiinsa. Sähkömagnetiikan oppimisessa käsitteellinen tieto osoittautui olevan välttämätön mutta ei riittävä ehto proseduraalisen tiedon kehittymiselle. Käsitteellinen esitieto selitti tilastollisesti merkitsevästi opintomenestystä lopputentissä, mutta kompleksiset ongelmanratkaisutehtävät eivät kuitenkaan merkittävästi lisänneet opiskelijoiden käsitteellistä ymmärrystä. Tulokset osoittivat, että 18 prosentilla opiskelijoista oli johdonmukainen tai lähes johdonmukainen naiivi käsitemalli Newtonin kolmannesta laista sähkömagnetiikan viitekehyksessä. Tämä malli oli yhteydessä opiskelijoiden menestymiseen käsitetestissä. Tutkimukseen osallistuneista 16 prosenttia kärsi matematiikka-ahdistuksesta. Matematiikka-ahdistuksen huomattiin vaikuttavan opiskelijoiden proseduraaliseen suoritukseen mutta ei käsitteelliseen.

Tämän väitöskirjan tulokset osoittavat tarvetta laajentaa käsityksiä siitä minkälaista tietoa arvostetaan ja arvioidaan teknillistieteellisissä opinnoissa sekä mitä matemaattisen kyvykkyyden osatekijöitä tulisi tukea, jotta diplomi-insinööriksi valmistuvien teoreettinen ja tekninen asiantuntijuus kehittyisivät korkealle tasolle.

Avainsanat käsitteellinen ja proseduraalinen tieto; sähkömagnetiikka; matematiikka-ahdistus; teknillistieteellinen opetus

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Preface

This thesis was carried out at the Department of Radio Science and Engineering of the Aalto University School of Electrical Engineering. My work was financially supported in part by the Aalto University Professional Development and the School of Electrical Engineering.

I would like to thank my supervising professor Ari Sihvola for his contribution to the writing process of this thesis. I am very grateful of his expertise and warm support that I have received in every step of the way. I have been privileged to work under his skillful and inspiring guidance. He has introduced me to the fascinating world of electricity and magnetism. I have come to realize how these fundamental interactions of nature are responsible for most of the phenomena we encounter in daily life. I have also learned how difficult and complex subject electromagnetics is to learn and the various difficulties students encounter when studying the subject. I hope this thesis will bring new information on learning of electromagnetics and advancing of pedagogical practices.

My sincere thanks go to the instructors of this thesis, Professor Jari Lavonen and Docent Kalle Juuti for their effort and insightful comments. My thanks go to my collaborator Henrik Kettunen. I am grateful to my preliminary examiners Professor Lauri Kettunen and Docent Pekka E. Hirvonen for their constructive comments. I would also like to thank Michelle Chote for language corrections.

I am thankful to the members of the SEAL research group at the Stanford University, especially Professor Richard Shavelson and Jon Shemwell for their comments and discussions related to physics education, conceptual change research, as well as my ongoing study. I learned a lot during my visit.

My thanks go to Anna-Kaarina Kairamo and Seija Räisänen for helping me with the administrative issues and making the visits to foreign universities possible. I want to express my gratitude also to the members of the SÄMA study group with whom I shared the joys and sorrows of the graduate studies.

I am deeply grateful to my family, my dear husband Jussi and our wonderful children Otso, Oona, and Elmo. Your love and invaluable support have carried me through calm and the storm. This thesis is dedicated to my Mother, Liisa. She would have been happy to see this day.

Otaniemi, Espoo, 1st of June 2011

Johanna Leppävirta

Contents

List of publications

The current thesis is based on five publications, referred to in the text as Studies 1-5.

1. **Leppävirta, J**., Kettunen, H. & Sihvola, A. (2011) Engineering students' conceptual knowledge of electro- and magnetostatics. *Proceedings of the Progress in Electromagnetics Research Symposium* (PIERS), 1661-1664, Marrakesh, Morocco.

2. **Leppävirta, J.**, Kettunen, H. & Sihvola, A. (2010). Complex problem exercises in developing engineering students' conceptual and procedural knowledge of electromagnetics. *IEEE Transactions on Education*, 54(1), 63-66.

3. **Leppävirta, J.** (in press). The effect of naive ideas on students' reasoning about electricity and magnetism. *Research in Science Education*. doi: 10.1007/s11165-011-9224-7

4. **Leppävirta, J.** (2007). Developing an instrument to measure engineering students' mathematics anxiety when learning electromagnetics. *Proceedings of the ReflekTori2007, Symposium of Engineering Education*, 81-91, Espoo, Finland.

5. **Leppävirta, J.** (2011). The impact of mathematics anxiety on the performance of students of electromagnetics. *Journal of Engineering Education*, 100(3), 1-20.

Contribution of the author

All of the phases of this thesis have been carried out independently by the author. I have been responsible of designing the study and collecting the CSEM and EMARS data for the analysis.

The complex problem exercises and the exam questions were designed by Professor Ari Sihvola. The descriptions of the exercises (see section 4.2) and the analyses of the complex problem exercises (see section 5.1) were written in cooperation with the co-author Henrik Kettunen.

The CSEM and EMARS analyses have been carried out solely by the author. As the first author of all manuscripts, I have had the main responsibility for writing the publications, with active participation of the co-authors.

Abbreviations

α	Alpha; Cronbach's index of internal consistency
β	Standardized multiple regression coefficient
χ^2	Computed value of a chi-square test

f	Frequency
F	Fisher's F ratio
M	Mean (arithmetic average)
N	Total number in a sample
n	Number in a subsample
ns	Nonsignificant
p	Probability
r	Pearson product-moment correlation
r^2	Pearson product-moment correlation squared; coefficient of determination
R^2	Adjusted multiple correlation squared: measure of strength of relationship
SD	Standard deviation
t	Computed value of t-test
z	A standard score; difference between one value in a distribution and the mean of the distribution divided by the standard deviation.

ABET	Criteria for Accrediting Engineering Programs
ANOVA	Analysis of variance (univariate)
ASSIST	Approaches and Study Skill Inventory for Students
CA	Circuit Analysis
CFA	Confirmatory factor analysis
CFI	Comparative fit index
CSEM	Conceptual Survey of Electricity and Magnetism

DF	Degree of freedom
ECF	Electric charge and force
ECTS	European Credit and Accumulation System
EFA	Exploratory factor analysis
EFF	Electric field and force
EM	Electromagnetics
EMARS	Electromagnetics Mathematics Anxiety Rating Scale
EPE	Electric potential and energy
MFF	Magnetic field and force
NL	Newton’s laws
PER	Physics Education Research
SRMR	Standardized root mean square residual
TLI	Tucker-Lewis fit index

1. Introduction

In the past decade, Finnish universities have gone through significant changes. Globalization, alterations in the operational environment, as well as growing cooperation with foreign universities and research institutes have created a need for universities to become more independent and autonomous in order to compete and function more flexibly. The Finnish higher education reform, which came into operation in 2010, has provided universities with more legal and economical independency from the government. One of the goals of the reform has been to improve operational preconditions of universities in order to respond to their needs. The competition for international funding has also increased the importance of various university rankings. International rankings do not only measure research performance, but also human competitiveness. The study by Bowman et al. (2009) revealed that rankings provided substantial admission benefits, especially for institutions ranked above the top 25.

The radical changes in higher education have led to universities needing to educate an increasing and more diverse group of students to be successful in science, mathematics and engineering. According to the Criteria for Accrediting Engineering Programs (ABET) standards, engineering students need to become reflective thinkers and effective problem solvers (Engineering Accreditation Commission, 2011). Students are expected to have a firm understanding of mathematics and basic sciences on the one hand and engineering practice on the other. The task is not easy.

Recent studies show that there are various factors, such as lack of sufficient interest, under-preparedness and poor study skills that cause students to switch from science, mathematics, and engineering majors to other disciplines (Li et al., 2008; Seymor & Hewitt, 1997). However, most of the attrition seems to occur when students are studying pre-engineering mathematics and science courses (Marr et al., 1999; Seymor & Hewitt, 1997). The studies conducted by Levin and Wyckoff (1988) among engineering students revealed that the ability in mathematics was found to be the best single predictor of engineering success.

The national survey (Sammalisto, 2009) conducted in Finnish engineering universities in 2005–2007 showed that 36% of students perceived the pre-engineering mathematics courses as being an obstacle to their progress in engineering studies. Erkkilä (2009) studied second-year engineering students' learning strategies in the same national survey. The study used the Approaches and Study Skill Inventory for Students (ASSIST) test developed by Entwistle at al. (2000). The results showed that 48% of students had a strong surface- or strategic-approached orientation to studying. The surface-approached orientation was characterized by memorizing, repetition, and reproducing. Strategic-approached orientation, on the other hand, was clearly focused on achievement and learning the topics that are considered relevant for passing courses. Strategic executors (27%) who had strong strategic- and surface-approached orientation progressed best in the light of the number of the European Credit and Accumulation System (ECTS) credits. Students with a surface-approached orientation (21%) had both the lowest amount of studies executed and most negative experiences of studying. These findings suggest that students' study strategies and perceptions of pre-engineering mathematics and science courses do not significantly enhance students' skills to become effective problem-solvers and reflective thinkers.

In recent years there has been a growing interest in engineering education research to study cognitive aspects of learning (DiGregorio, 2006; Taraban et al., 2007a; Taraban et al., 2007b). The research has put more emphasis on understanding and measuring engineering student learning, rather than teaching (Qualters et al., 2008). New tools have been developed to systematically monitor, explain, and subsequently improve students' learning. Electromagnetics is an ideal subject for studying engineering students' knowledge construction since it is often viewed as one of the most abstract and conceptually difficult areas of electrical engineering education (Ulaby & Hauck, 2000). It constitutes, however, the basic foundation for electrical engineering theories and principles. Successful learning in electromagnetics requires a variety of different skills. Students need to use powerful mathematical tools, for example vector algebra, and differential and integral calculus. They need to understand abstract concepts of the physical systems, such as electric and magnetic field structures, and they also need to understand visual representations of principles and applications. In addition, engineering students need to develop practical problem-solving abilities to build a fundamental link between engineering discipline and theory. In spite of the important role of electromagnetics in electrical engineering education, many universities report that electromagnetics courses are perceived as abstract and irrelevant. Furthermore, students struggle with mathematics and have been shown to have motivational difficulties when studying the subject (Bagno & Eylon, 1997; Bunting & Cheville, 2009; Hoburg, 1993; Marr et al., 1999; Mukhopadhyay, 2006; Ulaby & Hauck, 2000).

This thesis has been conducted in the turbulence of the university reform and merging of universities. The Aalto University was created in 2010 from the merger of three Finnish universities: The Helsinki School of Economics, the Helsinki University of Technology, and The University of Art and Design Helsinki. The vision of the new Aalto University is to be one of the leading institutions in the world in terms of research and education. The emphasis is on creating an international and multicultural learning and research environment that facilitates lifelong learning.

In order to meet these educational challenges and advancing pedagogical practices more research is needed to understand the specific factors underlying the learning of engineering undergraduates. For example, how students understand engineering concepts or what makes them effective problem-solvers? In order to create appropriate conditions for effective learning we need to recognize what kind of cognitive and affective barriers there are for learning mathematically demanding subjects in the field of engineering. Although extensive amount of research in science and engineering education has been conducted on the development of students conceptual knowledge, rather little is known about engineering students' procedural knowledge, and especially how conceptual and procedural knowledge alternate and contribute to the development of expertise. Further, the majority of the studies of conceptual difficulties of students have been conducted in Anglo-Saxon counties and to a lesser degree in small countries. Although conceptual difficulties of students in the domain of science and engineering appear to be somewhat universal, we would expect some cultural differences in the learning of new concepts and procedures.

The present thesis has elements of three different areas of research. Firstly, the thesis is research of higher education, which examines educational developments that occur at universities, polytechnics, colleges, and vocational institutions. Secondly, the thesis is more precisely research of engineering education, which is discipline-based education research that aims to develop activities to enhance the teaching and learning of knowledge that is related to the professional practice of engineering. Thirdly, the thesis has elements of physics education research (PER). The primary goal of PER is to develop pedagogical techniques and strategies that will help students overcome preconceptions and to learn physics more effectively (McDermott & Redish, 1999).

The aim of this thesis is to assess undergraduate engineering students' proficiency in electromagnetics in a comprehensive way. Three components of proficiency are assessed: procedural, conceptual, and affective. The successful learning of electromagnetics requires procedural knowledge (i.e. the ability to effectively solve domain problems) as well as conceptual knowledge, the actual comprehension of the physical concepts and the relations between them. The particular interest of the study is to examine how procedural and conceptual knowledge interact and how they together impact on students' overall performance. In affective level, the focus is on mathematics anxiety that has been recognized to have a negative effect on students' academic performance.

This thesis summary consists of five sections. Section 2 presents the theoretical background. Sections 3 and 4 present the research questions and methods. The results are presented in section 5. First, the overall performance of the students is described following the results of each study. Finally, section 6 describes the general discussion of the thesis.

2. Background

2.1 Procedural and conceptual knowledge

Proficiency in problem-solving and computation has long been one of the main goals in many domains of engineering education. *Procedural knowledge*, which is considered by cognitive psychologists as “knowing how” knowledge, is the ability to utilize knowledge, methods, and rules dynamically and successfully within relevant representation forms (Anderson, 1985; McCormic, 1997). Procedural knowledge fundamentally has a problem-solving orientation, which means that the cognitive activities are purposeful and directed to achieving goals (Anderson, 1985).

In science education research, the concept of problem-solving has been used in contrast with conceptual knowledge more commonly than procedural knowledge. In some studies, procedural and problem-solving knowledge are even referred to as the same construct (Heyworth, 1999; Taraban et al., 2007a; Taraban et al., 2007b). However, few studies, such as Jong (1986) and Millar (1994), have defined procedural knowledge in science education to mean “the thinking behind doing” of science. This concept is tightly embodied in action, including skills such as understanding aims and purposes, use of instruments, ability to carry out standard procedures and to interpret the results. In the engineering context, Case and Marshall (2004) use the concept of algorithmic approach (in parallel with procedural) when referring to students’ strategies for identifying and applying calculation methods for solving problems.

Although the concept of procedural knowledge has been used more often in the context of mathematics education than science education, we have chosen to use this concept in the domain of electromagnetics for two reasons. Firstly, electromagnetics is heavily based on mathematical ideas, such as Maxwell’s equations. We would expect students’ proficiency in electromagnetics to be strongly dependent on procedural as well as conceptual knowledge. Secondly, the concept of problem-solving is highly complex and contains various levels (Jonassen, 2000). It can be seen as an overall concept that includes conceptual and procedural knowledge, as well as strategic knowledge, which refers to students' metacognitive skills that control procedural and conceptual knowledge (McCormic, 1997). Strategic knowledge consists of, for example, students' ability to decide what to do and when, and the ability to formulate, represent, and solve problems. For this thesis, we have chosen the concept of procedural knowledge, as it is more concise dimension (usually a very clearly defined model in the studies of mathematics, see for example Byrnes & Wasik, 1991; Rittle-Johnson et al., 2001) for studying students' proficiency in electromagnetics. However, we acknowledge that mathematical proficiency does not necessarily mean the same thing as being proficient in physics, since being exposed to solving real-life problems, students need to use various problem-solving skills in order to overcome preconceptions to learn physics effectively.

In the context of mathematics, procedural knowledge has been defined to consist of two separate components. The first part includes the knowledge of mathematical format and symbol representation system and the second part the algorithms, procedures and rules for solving mathematical tasks (Hiebert & Lefevre, 1986). Kilpatric et al. (2001), writing of children's mathematical performance, refer to *procedural fluency* as a skill in carrying out procedures flexibly, accurately, efficiently and appropriately. Cognitive theories talk about fluency and automaticity as important characteristics of expertise (Bransford et al., 1999; Byrnes & Wasik, 1991). Fluent retrieval means that appropriate procedures can be easily retrieved from memory freeing capacity for learning more complex procedures. However, this procedure, also called proceduralization (Byrnes & Wasik, 1991), needs to be based on understanding, not in memorization. Mathematical procedures that are learned with meaning are procedures that are linked to conceptual knowledge (Hiebert & Lefevre, 1986).

Procedural knowledge of mathematics is rich in rules and strategies for solving problems, whereas *conceptual knowledge* is distinguished by relationships between pieces of information (Hiebert & Lefevre, 1986). Conceptual knowledge (also referred in literature as declarative knowledge) is defined as understanding of physical concepts, operations and relations. The student‘s knowledge, and comprehension of facts and methods are organized in a coherent way, and the student knows how concepts are interdependent and how they are applied in different contexts (Kilpatric et al., 2001). When students can identify these relationships, we can say that they have *conceptual understanding* (McCormic, 1997). For example, in the domain of electromagnetics, we expect students to understand the relationship among a charged particle and electric field or current and magnetic field. Although conceptual knowledge is considered as “knowing what” knowledge, it is not in any way a static stage. During the learning process, knowledge of particular networks of concepts, rules and problems expand and become more general. For example, a solved problem can introduce a new concept or rule (Haapasalo, 2003).

A central component in learning new concepts is the prior knowledge that influences the way new information is understood and scientific concepts are learned (Vosniadou, 2008). Science education research has produced a rich body of knowledge about students’ alternative conceptions or misconceptions. *Alternative conception* is defined as a concept or idea that is embraced prior to instruction and is inconsistent with the current scientific concept (Abimbola, 1988). The term misconception has commonly been used concurrently with the alternative conception term in the context of science education. Misconceptions are defined as students’ conceptions that produce systematic patterns of error (Vosniadou, 2002). In this theoretical framework, the conceptual change is considered a replacement of old conceptions for new (Vosniadou et al., 1999). The conceptual change approach has been traditionally applied in science education research. However, it appears that students are confronted with similar problems when learning mathematics and science (Vosniadou, 2008). Apparently students develop misconceptions based on everyday experience also in the context of mathematics, which facilitate some kinds of learning but constrain others. According to Abimbola (1988), the term alternative conception is more inclusive hence preferable term to be used in describing students’ conceptions in science. For this reason, the term alternative conception will be used throughout the current study.

Although conceptual change researchers disagree on how the science conceptions are organized and how they develop in the learning process there is a common agreement that some basic ideas (for example in physics) remain difficult for students even after substantial instruction (Brown & Hammer, 2008). Furthermore, students’ incorrect answers tend to group into a small number of alternatives and students show to gain confidence in their incorrect answers.

The way conceptual and procedural knowledge alternate in learning is highly complex (Engelbrecht et al., 2009; Haapasalo, 2003; Hiebert &

Lefevre, 1986; Stillings et al., 1995). Some cognitive theorists argue that conceptual and procedural knowledge need to be differentiated since they serve different cognitive functions (Byrnes & Wasik, 1991). Concepts represent order and relations, whereas procedures are carried out to attain goals (Anderson, 1985, p. 198; Hiebert & Wearne, 1986, p.201). Empirical arguments in the domain of mathematics, on the other hand, claim that conceptual-procedural dichotomy is necessary because studies show cases in which individuals have high levels of conceptual knowledge but lack procedural skill or vice versa (Byrnes & Wasik, 1991). There are also contradictory studies of whether task manipulations impact the performance of individuals for one area of knowledge but not for the other (see Rittle-Johnson et al., 2001; Schacter, 1989). Although some views claim that procedural and conceptual knowledge are independent (see e.g. Baker & Czarnocha, 2002; Nesher, 1986; Resnick & Omanson, 1987) the majority of researchers in the domain of mathematics seem to agree that there is an interdependent relationship between conceptual and procedural knowledge (Byrnes & Wasik, 1991; Haapasalo, 2003; Hiebert & Lefevre, 1986; Kilpatrick et al., 2001).

According to Hiebert and Lefevre (1986), conceptual knowledge of mathematics makes learning procedural skills easier and free up capacity for learning more difficult procedures. When skills are learned without understanding they are learned as unconnected pieces of knowledge and it can be difficult to get students to enter into activities to help them understand the reasons underlying the procedures (Hiebert & Lefevre, 1986; Kilpatrick et al., 2001). On the other hand, without sufficient procedural fluency, students have difficulties in deepening their knowledge of facts and ideas or solving mathematical problems (Kilpatric et al., 2001).

Byrnes and Wasik (1991) distinguish two approaches regarding the relationship between procedural and conceptual knowledge in the domain of mathematics. In the *simultaneous activation approach*, conceptual knowledge is seen as a necessary and a sufficient condition for correct use of procedures. This view argues that by enriching students' conceptual knowledge, students are enabled to detect errors in their procedures (Hiebert & Lefevre, 1986). Furthermore, if conceptual knowledge is low, procedures will be performed incorrectly. The contrasting view that Byrnes and Wasik (1991) introduce is the *dynamic interaction approach*. The conceptual knowledge is seen as a necessary but not a sufficient condition for acquiring procedural skill. Rich conceptual knowledge base helps to develop meaning for symbols and promotes recalling and using procedures. Once procedures are learned, however, they develop independently. Discrimination and generalization processes help learners to decide when and in which contexts to apply various procedures. The proceduralization process enables the procedures to become fluent and automatic, freeing capacity for learning new procedures effectively. Furthermore, procedural and conceptual knowledge interact in diachronic cycles over time, not concurrently when learner is engaged in problem-solving. Rittle-Johnson et al. (2001) have similar findings but introduce the *iterative model* where conceptual and procedural knowledge appear to develop in a hand-over-hand process. According to the authors, either conceptual or procedural knowledge may begin to develop first. In addition, task manipulations, such as receiving prompts, improve students' procedural as well as conceptual knowledge. Both studies, Byrnes and Wasik (1991) and Rittle-Johnson et al. (2001), were conducted among primary and secondary school students and the mathematical tasks examined were fractions.

As Hiebert and Lefevre (1986) state, students are not fully competent in mathematics if either kind of knowledge is deficient or if they remain separate entities. Yet, more recent studies strongly indicate the importance of conceptual knowledge prior to procedural proficiency. Undergraduate mathematics students that were taught with a "conceptual" approach performed better than the "instrumental" group on tasks involving both conceptual and procedural knowledge (Chappell & Killpatrick, 2003; Pesek & Kirshner, 2000). More research is clearly needed in order to better understand the way procedural and conceptual knowledge alternate and affect the performance of students.

2.2 Affective factors

Being competent in mathematics and science involves not only cognitive aspects but affective components as well (Kilpatrick, 2001). Recent studies point out the need to include other than purely cognitive dimensions to understand the relationship between conceptual and procedural knowledge. Bergsten (2006) studied students in their first calculus course solving tasks on limits of functions. The study was a qualitative video study of six undergraduate engineering students. The students with a conceptual approach were more confident with expressing their own reasoning.

Students with a strong procedural approach were more likely to refer to an external authority to confirm their reasoning. Engelbrecht et al. (2005) studied a group of first-year university students attending a course in applied calculus. The results showed that students were more confident in their ability to answer conceptual problems than procedural problems. The authors suggest that the reason for this somewhat unusual result was that the course strongly emphasized understanding and interpretation.

Mathematical self-concept has been shown to be a positive predictor of persistence in mathematics (Sherman, 1983). The self-concept refers to students' perception of their own ability to perform well in mathematics and to learn new topics (Sax, 1994; Townsend & Wilton, 2003). Sax (1994) conducted an extensive study on college students' mathematical self-concept. The study revealed that both male and female students majoring in scientific or technical fields experienced overall gains in mathematics self-confidence even when their initially higher levels of mathematics confidence were partialled out. Crawford et al. (1994) studied mathematics students at universities and their study revealed, however, that over 75% of students perceived of mathematics as a fragmented body of knowledge, and learned it using a repetitive and surface approach. Their follow-up study (Crawford et al., 1998) also revealed that students holding different conceptions of mathematics adopted different approaches to learning it. Coherent conceptions of mathematics (e.g. seeing mathematics as a logical system which helps explain the things around us) was associated with deep approaches to learning mathematics, whereas fragmented conceptions (e.g. mathematics is figuring out problems involving numbers) led to surface approaches to learning mathematics.

Many studies have reported the negative effects of mathematics anxiety on students' performance and achievement in mathematics (Ashcraft & Kirk, 2001; Ma, 1999; Ma & Xu, 2004). Mathematics anxiety is defined as a feeling of tension and anxiety that disrupt the manipulation of numbers and the solving of mathematical problems in both everyday life and academic situations (Richardson & Suinn, 1972; Tobias, 1994). The meta-analysis conducted by Ma (1999) among students across Grades 5 to 12 showed an average population correlation between mathematics anxiety and mathematics achievement of -.27, whilst acknowledging that the research exhibits an uncertainty regarding the causal priority between mathematics anxiety and mathematics achievement. The question has been that of whether high anxiety is a *cause* of low mathematics achievement, or whether high anxiety is an *effect* of low mathematics achievement. Ma and Xu (2004) found in their longitudinal analysis among middle and high school students that prior low mathematics achievement had a weak but significant relation to later mathematics anxiety throughout their school life (Grades 7 to 12) . For example, low achievement in Grade 7 was related to higher scores in mathematics anxiety in Grade 8. In contrast, prior high mathematics anxiety was not the cause of later low achievement in mathematics.

Ashcraft and Kirk (2001) examined the possible cognitive consequences of mathematics anxiety on undergraduate psychology students. Their study showed a momentary reduction in the available working-memory capacity of high-mathematics anxiety individuals when their anxiety was aroused. This was especially significant in mathematical situations where procedural knowledge was required - for example carrying, borrowing, or sequencing, and keeping track in multi-step problems. Higher levels of mathematics anxiety were related to lower available working memory capacity, not as an inherent characteristic, but as a temporary reduction in processing capacity. Rayner et al. (2009) re-assessed the previous results of the negative relationship between mathematics anxiety and mathematics performance in complex-problems, and used pre-service teachers as their subjects.

2.3 How proficient are undergraduate engineering students?

It is difficult to form a comprehensive overall picture of engineering students' procedural knowledge based on the research literature. Some studies, however, can be found that reveal some aspects of procedural knowledge of undergraduate engineering students. Marr et al. (1999) conducted a study among engineering majors in an introductory electromagnetics course. The results were based on interviews and analyses of quiz answers. The study showed that first-year engineering students used more surface-type learning strategies when solving problems, such as matching and memorizing operational equations for exams. Students' test preparation was characterized by memorizing equations and lacked any referents. Many students were able to apply an appropriate formula, but did not show understanding of the basic principles. The success depended on whether students remembered the correct formula for the problem and calculated it correctly.

Marra et al. (1998) measured first-year engineering students' cognitive development based on the Perry model. The Perry model proposes that the development goes through several stages where students' reasoning evolves from dualistic "right or wrong" thinking towards diversity. The study showed that first-year students were at Perry level 3 and 4 where they were comparing several possibilities, yet expecting the teacher to provide the correct answer. Taraban et al. (2007a; 2007b) conducted a study among science and engineering majors enrolled in the thermodynamics course. The study observed students' learning strategies as if preparing for an exam. The students were using both interactive and text-based instructional software. The study showed that students made significantly more lower-level than higher-level cognitive verbalizations, proposing that they were processing the materials with a surface-approached orientation. The majority of students approached the materials using very simple cognitive strategies, such as repeating word by word, memorizing sentences, paraphrasing, and constructing very basic summaries of the materials. The results revealed deficiencies in inference and explanation, as well as drawing conclusions. Interactive exercises and quiz problems, however, improved students' engagement in cognitive activities. Similarly, Case and Marshall (2004) identified procedural deep and procedural surface approaches to learning among second-year engineering students. Both strategies were focusing on problem-solving, but the former involved the intention to gain understanding, whereas the latter merely intended to pass the exam.

Assessing the conceptual knowledge of students with concept inventories has become common also in engineering education. The traditional multiple-choice concept inventories used in physics education research, such as Force Concept Inventory (FCI) (Hestenes et al., 1992), have been adapted to engineering education as well. Concept inventories have been developed for few electrical engineering subjects, for example, for signals and systems (SSCI) (Wage et al., 2005), electric circuits (ECCI) (Rahman & Ogunfunmi, 2010), and electricity and magnetism.

In the domain of electricity and magnetism, several multiple-choice instruments are widely used (Ding et al., 2006; Maloney et al., 2001; Notaros, 2002). The instruments are similar to one another, but differ in the specifics of the different contents. The Conceptual Survey of Electricity and Magnetism (CSEM) (Maloney et al., 2001) was developed to measure students' general knowledge of electricity and magnetism. The CSEM instrument provides an estimate of students' common sense conceptions in this domain, and it can be used for determining how well students develop understanding of the important terms, relations and physical formalism.

Although considerable amount of research has been conducted on students' preinstructional ideas in the domain of electromagnetics, there are not yet clearly defined alternative conceptions about electricity and magnetism compared to, for example, mechanics (Maloney et al., 2001). In mechanics, students' alternative conceptions of motion and force, for instance "force as a mover", are shown to be strongly held, and affect the way students understand natural phenomena and scientific explanations (diSessa, 1993). The alternative conceptions in mechanics, however, appear to influence the way electromagnetic concepts are understood. Bagno and Eylon (1997) studied problem-solving skills and conceptual knowledge of high-school students majoring in physics and preparing for their matriculation examination. The study revealed that 40% of the students attached acceleration of a charged particle only to a change in the magnitude of velocity and not in its direction. This is a well-documented alternative conception in mechanics (Bagno & Eylon, 1997).

Another pervasive alternative conception from mechanics, called Ohm's p-prim "more effort creates more results", interferes with students' reasoning (diSessa 1988). The conceptual survey by Maloney at al. (2001) showed that instead of applying Newton's third law or the symmetry of Coulomb's law, the Ohm's p-prim provided an applicable explanation for 30% of the students learning electromagnetics. In the example of two electric point charges, the incorrect belief is that when the net charge of the first point charge is increased, it exerts greater force only on the second point charge but does not affect the force on the charge itself. The alternative explanation fails to consider the symmetry of the electric forces. The findings show also that students are reluctant to apply laws from mechanics, for example Newton's laws, in electricity and magnetism (Maloney et al, 2001; Planinic, 2006).

The study by Bagno and Eylon (1997) also revealed that students' knowledge representation of electricity and magnetism was deficient. It did not include central relationships (e.g. Maxwell's equations) in any form, neither mathematically nor qualitatively. Instead, the majority of students overemphasized subsidiary ideas, for example Ohm's law, at the expense of more central relationships. Furthermore, students lacked a coherent organization of concepts and relationships in electromagnetics in order to facilitate the process of retrieval. Most students represented the relationships only in mathematical form and did not have access to more qualitative representations. The study gives a fairly comprehensive view of students' knowledge representation in the domain of electricity and magnetism prior to entering colleges and universities.

A few studies in engineering education research target both conceptual and procedural knowledge and the relation between them. Steif (2003) compared students' performance on a concept inventory and solving of multifaceted problems. The students were attending the Statics course in engineering mechanics. The study did not consistently find that students who made a particular error in the concept inventory had a similar tendency to make the corresponding error in the multifaceted problem. For example, half of the students that made no errors in the concept inventory made errors on the multifaceted problems. These findings support the dynamic interaction view that conceptual knowledge is a necessary but not a sufficient condition for procedural knowledge. Buck et al. (2007), on the other hand, found a significant correlation between concept inventory performance and the final exam. The study was conducted among second-year university students participating in a signals and systems course. These findings support the simultaneous activation approach where conceptual knowledge is a necessary and a sufficient condition for procedural knowledge. The students with high conceptual knowledge committed fewer procedural errors than students with less conceptual knowledge. However, conceptual knowledge did not produce erroneous performance on a routine Fourier transform, but did have an impact on accuracy in complex problem-solving. The solving of complex multifaceted problems requires conceptual insight in order to deconstruct the problem into relevant sub-problems, whereas, a routine Fourier transform requires rote memorization and recall in order to produce erroneous performance.

The aim of the study by Engelbrecht et al. (2009) was to find out how first-year engineering students attending a mathematics course solved problems designed to be solved with a conceptual or procedural approach. The results were surprising. Some students attempted to also solve the conceptual problems procedurally. The usage of procedural solutions to conceptual problems did not indicate poor understanding of mathematics. On the contrary, when conceptual problems were "proceduralized", the problem-solving required skillful mathematical computations and much more effort than a more conceptual approach. The study suggests that the ability to decide on which approach is the most appropriate, requires deeper conceptual and procedural knowledge from students.

2.4 Summary

Based on these studies we can conclude that first-year engineering students rely mostly on lower-level procedural processing. The goal is to try to understand the content but students are not yet cognitively prepared to find inferences, to pose questions, to explain or draw conclusions. First- and second-year engineering students possess conceptual knowledge but they have problems with properly understanding basic relations and applying concepts in different contexts. They also have several persistent alternative conceptions that interfere with the learning of scientific concepts. Only a few studies, however, address the interrelations between procedural and conceptual knowledge and how these components impact on performance.

Students entering engineering universities have generally positive perceptions about mathematics and perceive it to be important to their engineering studies. Engineering students also gain mathematical confidence along with acquisition of knowledge, yet limited research has been done of mathematics anxiety impacting on engineering students' performance.

3. Research questions

Previous research suggests that electromagnetics courses are perceived as abstract and irrelevant. Students struggle with heavy mathematics and have been shown to have motivational difficulties when studying the subject.

The overall aim of the thesis was to assess engineering students' proficiency in electromagnetics. Three aspects of proficiency were assessed: procedural, conceptual, and affective. The aim was also to examine how procedural and conceptual knowledge are related, and how together they impact on students' overall performance. At the affective level, the focus was on mathematics anxiety, which has been recognized to have a negative effect on students' academic performance. Figure 1 gives an overview of the studies. The research questions of the individual studies were

i) How conceptually proficient are students of electromagnetics before and after instruction? Is there a relationship between procedural and conceptual knowledge? (Study 1)

ii) Does exposure to complex problem exercises improve students' procedural and conceptual knowledge of electromagnetics (Study 2)?

iii) Do students have consistent alternative conceptions in electromagnetics and how are these possible alternatives related to performance (Study 3)?

iv) Do engineering students suffer from mathematics anxiety? Does mathematics anxiety have an impact on students' performance (Study 4 and 5)?

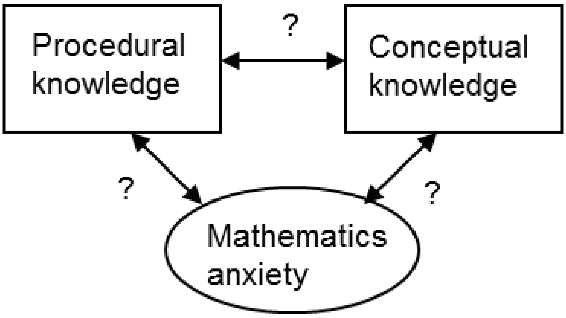

Figure 1. The research questions presented graphically. The two-headed arrows depict direct relations between constructs.

4. Methods

This study was conducted with a correlational research approach. Correlational research is concerned with achieving a fuller understanding of the complexity of phenomena. The approach explores behavioral patterns by studying the relationships between the variables that are expected to be related (Cohen & Manion, 1989). This study has taken mainly a relational approach, seeking to study the relationships, rather than trying to make predictions of students' performance. The study of mathematics anxiety (Study 5) also used a causal comparative approach, which focuses on making group comparisons (Mertens, 2005). Students' performance was compared between groups of high vs. low anxiety. The advantage of correlational research is that it discovers or clarifies relationships and achieves some degree of prediction. The correlational research, however, does not establish cause-and-effect relationships.

4.1 Sample course

Electromagnetic field theory is taught at the Helsinki University of Technology[1], Finland, in two one-semester courses (Static and Dynamic Field Theory) to second-year students participating in the Electrical Engineering program. The data were collected during the Static Field Theory at the Helsinki University of Technology, in autumn 2007. The aim of the course was to learn the fundamental concepts of electricity and magnetism and to apply these concepts to solving various field problems. In particular, the content included Maxwell equations in statics, electrostatic field and scalar potential, magnetostatic field and vector potential, static currents, and capacitance, inductance, and conductance. The course

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[1] The Helsinki University of Technology became the Aalto University School of Science and Technology from the beginning of 2010.

focused on quantitative problem solving, applying the skills to basic engineering problems, and explaining natural phenomena. The prerequisite mathematics course that the students were expected to have passed prior to the Static Field Theory course contained the following topics: complex numbers, matrix algebra, linear systems of equations, basics of differential equations and the Laplace transform, differential and integral calculus of vector-valued functions, vector fields, and curvilinear coordinates. The textbooks used in these pre-engineering mathematics courses were Adams (2010), Lay (2000), and Kreyszig (2010).

The course consisted of lectures, complex problem exercises, project work, and a final exam. Students were able to participate in tutorials, where they solved standard textbook problems with the help of an assistant. The complex problem exercises were compulsory and more complex and demanding than the exercises solved at tutorials. A Finnish-language textbook (Lindell & Sihvola, 2007) and an exercise book (Sihvola, 2005) about Static Field Theory were used during the course.

4.2 Performance measures

The performance of the students before, during, and after the Static Field Theory course was measured with complex problem exercises and two separate tests: a concept test and a final exam.

The complex problem exercises

The problem-solving exercises (see Appendix) were designed to develop complex skills. The problems were not standard textbook problems, which could be solved by recognition and recall. Solving complex problems required the ability to identify and formulate the precise problem from the given scenario. The problems included various procedures that involved successful application of fundamental concepts. There were altogether five problem-solving exercises that were returned one at a time during the course. The exercises followed the course themes and were designed to cover the main fundamental concepts and procedures of basic static field theory. The students were awarded points for the solved exercises, and the total exercise score made up 26% of the final grade.

The first problem was purely a mathematical one. It was a volume integration exercise in the spherical coordinate system over an inhomogeneous density. This exercise tested the mathematical skills of the students required on the course. *The second* exercise was a slightly complicated visualization problem. The task was to visualize the potential and the electric field of a combination of four point charges. There were no symmetries in the charge distribution so the visualization had to be three dimensional. Students were encouraged to build actual models. No computations were needed. *The third* problem considered electrostatics. A point charge was located close to a grounded conducting sphere. Students were asked to find the radius of the sphere for which the maximum value of the electric field on the surface of the sphere has its minimum value. Students were supposed to find out that they should apply a method of image charge, also known as Kelvin inversion. *The fourth* exercise was an approximation problem where the task was to find the leak resistance between the electrodes of a two-conductor line. *The fifth* problem considered magnetostatics. The students were asked to study the magnetic field caused by a current loop. The loop was approximated by a magnetic dipole and this approximative solution was compared with the exact solution. The exact solution was somewhat complicated and it required computing numerical values of elliptic integrals using some mathematical software.

The CSEM

The conceptual learning gains were measured by using the Conceptual Survey of Electricity and Magnetism (CSEM) concept test (Maloney et al., 2001). The CSEM test is a broad instrument which evaluates the knowledge of electric charge, electric potential, electric and magnetic fields and force, and Newton’s laws in an electromagnetic context. The CSEM consists of 32 multiple-choice questions. In this study, the last four questions (29–32) were omitted since they deal with the dynamic field theory, which was not covered in this introductory electromagnetics course. A three point Likert scale of confidence from 1 (*guessing*) to 3 (*highly confident*) on each item was added to the original CSEM instrument. A Finnish translation of the CSEM test conducted by the Department of Physics and Mathematics at the University of Eastern Finland was used. The translation is highly reliable and has been used over several years for assessing students in the department. Some minor changes to the wording (for example Finnish word “particle” was changed to “charge”) were done in order to make the test more suitable for the domain of electrical engineering. The test was used as a pre- and post-test.

For the analysis, the CSEM items were classified into five different conceptual areas, based on classification by Planinic (2006).

1) *The Electric charge and force* (ECF) area deals with charge distribution on conductors and insulators, Coulomb’s force law, and electric field and force superposition (questions 1-3, 5, 6 and 8).
2) *The Electric field and force* (EFF) area concerns questions about the force caused by an electric field, the superposition of electric fields, and the effect of induced charge on the electric field (questions 9 and 12-15).
3) *The Electric potential and energy* (EPE) area investigates knowledge of the concept of electric potential and its relation with electric field, work and electric force (questions 11 and 16-20).
4) *The Magnetic field and force* (MFF) area measures conceptions of magnetic field, magnetic field caused by a current, and magnetic field superposition (questions 21-23, 25, 26, and 28).
5) *The Newton’s laws* (NL) area measures knowledge of all three Newton’s laws in the context of electricity and magnetism (questions 4, 7, 10, 24, and 27).

The CSEM is a well-designed and validated instrument, in which the items have been tested to measure the understanding of the key concepts of electricity and magnetism. The item difficulty index, which is the measure of the difficulty of a single test question, was reported to vary between .10 and .80 (Maloney, 2001). The acceptable level is in the range of .3 to .9 (Ding et al., 2006). The item discrimination index measures the discriminatory power of each item in the test. The index of the CSEM items ranged between .1 and .55, which is acceptable (Maloney, 2001). The Kuder-Richardson reliability index is a measure of the self-consistency (re-test reliability) of a whole test. This index is a measure of how consistently the test will reproduce the same score under the same conditions (Ding et al., 2006). The reliability index for the CSEM was around .75, which is an acceptable value. Tests with a reliability index higher than .70 are considered to be reliable for group measurements (Ding et al., 2006).

Overall, the results indicate that the CSEM test is a valid and reliable instrument for research and classroom assessment purposes.

Although the CSEM is widely used and carefully validated instrument, also some critique of its credibility has been suggested. The study by Saarelainen et al. (2007) revealed that students performed relatively well in the CSEM test, but when the questions were slightly modified, the more detailed interviews revealed significant flaws in their understanding of the field. We need to bear in mind that concept inventories only give a general overview of students' understanding, but cannot explain more profound conceptual structures of students.

The exam

The final exam consisted of three problem-solving exercises and the CSEM post-test. Together, they aimed to assess basic concepts and procedures learned during the field theory course. The problem-solving exercises (see Appendix) were designed to measure students' procedural knowledge and were similar to complex problem homework exercises. Naturally, exam exercises required much less work, since they needed to be completed in limited time.

The distinction between procedural and conceptual knowledge measured by the problem-solving exam exercises is less clear than in the CSEM concept test, which is considered to measure purely students' conceptual understanding. Although meant to assess students' procedural knowledge, the problem-solving exercises clearly include elements of conceptual knowledge as well. For example, understanding definitions and principles, such as Gauss' theorem, and being able to select proper mathematical methods requires conceptual understanding. However, the main task in the problem-solving exercises was to choose a proper mathematical formula, use the formula accurately, compute each step, establish possible directions, and to arrive at a solution. We consider all these steps to require procedural knowledge and therefore expect the problem-solving exercises to measure relatively well students' procedural understanding in the context of electromagnetics.

The first problem-solving exercise was a computation of a volume integral of the divergence of given vector function and also an integral of a normal component of the same function over the closed surface of the given volume. Students should realize that these two integrals should give the same result which was a verification of Gauss' integral theorem. *The second* problem considered the image charge principle in electrostatics. Two point charges with different values were located over a perfectly conducting half-space. The students were asked to compute the magnitudes and directions of forces exerted on both of the charges. By the image principle, the conducting half-space could be removed and replaced by two image charges. The total field one point charge sees was therefore a superposition of the fields of three other charges. *The third* problem was about magnetostatics. The students were asked to compute the total magnetic field along a certain axis caused by the currents of two infinitely long straight wires. The directions of the wires were perpendicular to each other but they did not lie in the same plane.

4.3 Mathematics anxiety scale

Engineering students are accustomed to using basic mathematical tools. A subject-specific mathematics anxiety rating scale for electromagnetics, the Electromagnetics Mathematics Anxiety Rating Scale (EMARS) (see Studies 4 and 5) was developed, since we anticipated that a more general mathematics anxiety instrument would not reveal the possible anxieties of those mathematically-able students. The EMARS investigates the underlying mathematics anxiety factors that affect the learning ability of engineering students of electromagnetics. Mathematics anxiety has been conceptualized as being multidimensional. Based on the MARS (also RMARS and MARS-R) scale (Richardson & Suinn, 1972), the Fennema–Sherman Mathematics Attitudes Scale (Fennema & Sherman, 1976), the Statistics Anxiety (STARS) Scale (Cruise et al., 1985), and previous research on mathematics anxiety, we identified five components of the broad view of mathematics anxiety in those studying electromagnetics. These components were: perceived anxiety, which encompasses the two components fear of asking for help and interpreting mathematical problems, questioning the subject itself (its usefulness), doubts about one’s ability to perform mathematical tasks (confidence) and students’ persistency to complete assigned tasks. For developing the questionnaire items, we asked students to write essays about their thoughts on learning mathematics and electromagnetics. The narratives of these essays were then used as the basis for designing the statements for the instrument.

The EMARS is a self-administered questionnaire consisting of 30 items. Using a Likert-type scale, the students are asked to express their opinion of the statements by choosing a number from 1 (*strongly disagree*) indicating "No anxiety" to 5 (*strongly agree*) indicating "Very high anxiety". Five subscales were derived from the 30 statements. The subscales are:

> *Usefulness* (5 items): Measures whether the student sees learning electromagnetics as useful and worthwhile. The high score suggests that the student sees no personal use in studying electromagnetics and no purpose in its professional application.
>
> *Confidence* (7 items): The category measures students' confidence and self-perceived ability to perform mathematics. The person scoring highly in this category finds mathematics unpleasant and tends to give up easily when confronted with difficult exercises.
>
> *Interpretation anxiety* (5 items): This category measures the anxiety experienced when a student is trying to solve mathematical problems and interpret the results. The person scoring highly in this category finds it very difficult to decide how to approach the mathematical problem and which concepts or formulas to apply. The student also has difficulties in using mathematical expressions.
>
> *Fear of asking for help* (5 items): This category measures the anxiety experienced when asking for help. A student with a high score shows anxiety when asking for help from other students or course instructors.
>
> *Persistency* (7 items): This category measures how much patience students have to try out different approaches and whether they are prepared to take time over solving mathematical problems; it also shows the students' tolerance for making mistakes. A high score suggests that the student easily becomes nervous and upset when confronted with difficulties in mathematical problem-solving. Such a student does not tolerate mistakes and believes that mathematics problems should be solved quickly.

The validity of the variable structure of the EMARS scale was tested by exploratory (EFA) and confirmatory factor analysis (CFA). The Kaiser-Meyer-Olkin (KMO) value (.78) and Bartlett's test of sphericity ($p<.01$) indicated that the data were appropriate for the factor analysis. The final exploratory factor analysis resulted in a four-factor solution. The total variance of the factor model was explained as follows: Factor 1 (persistency) 16.42%; factor 2 (usefulness) 13.01%; factor 3 (fear of asking for help) 12.26%; factor 4 (confidence) 9.52%. The model fitted well with the data set ($\chi^2 = 66.87$, DF=87, $p > .05$). The reliability coefficients for the fear of asking for help ($\alpha = .81$), persistency ($\alpha = .71$), and usefulness ($\alpha = .81$) were all acceptable/good. The reliability coefficient for confidence ($\alpha = .68$) was marginally below the accepted level of $\alpha \geq .70$ (see Kline, 1999). The four-factor model was confirmed by the collected data with confirmatory factor analysis (CFA). Types of goodness-of-fit measures for the post-test data were: $\chi^2 = 106.16$ (DF=71, $p = .004$), the comparative fit index (CFI) = .92, the Tucker-Lewis fit index (TLI) = .91, and the standardized root mean square residual SRMR = .08. These values indicate an acceptable fit between the model and the observed data (Schreiber et al., 2006).

4.4 Participants

The participants (N=133) were 118 males (89%) and 15 females (11%) (see Table 1). The mean age was 23.8 years and the standard deviation 4.6. Gender and age distributions were consistent with the overall population of students in the Faculty of Electronic, Communications, and Automation at the Helsinki University of Technology (Helsinki University of Technology, 2008). The average length of studies was 3.34 years, which is higher than what is expected of students attending a second-year field theory course. Nearly one third of the participants (29%) had already been studying more than three years. Prior to the Field Theory course, most of the students (approximately 90%) had completed the pre-engineering mathematics and physics courses, in addition to the basic Circuit Analysis (CA) course.

Table 1. Background information of the respondents

Variable	*M*(*SD*)
Gender M/F	118/15
Age	23.8 (4.58)
Length of studies[a]	3.34 (3.52)
Prior performance:	
Pre-engineering math[b]	2.38 (1.12)
Pre-engineering physics[b]	2.42 (1.20)
Self-rated math ability[c]	2.93 (0.73)

Note. M=male, F=female

[a] Length of studies thus far in years

[b] Performance in math and physics: mean of three courses (1-5 scale)

[c] Single-item variable, 1-5 scale, 1= low ability, 5= high ability

During the first lecture, students (*n*=103) were asked to fill out the CSEM and EMARS pre-test questionnaires. The post-test data of the CSEM and EMARS (*n*=102) were collected during the final exam. The number of students with matching pre- and post-test data was 88. The reason for the attrition is that not all students who attended the first lecture continued with the course. There were also students who intended to take the course, but were not present at the first lecture. The demographic information on the students, such as age, length of studies, prior performance in mathematics and physics, was obtained from the official student records. The measure of prior performance in mathematics was an average of the student's three pre-engineering mathematics courses (scale 1–5). The measure of prior performance in physics was calculated in the same way. The students' average performance in pre-engineering mathematics courses was 2.38, (SD =1.12, scale 1–5), and in pre-engineering physics courses was 2.42 (SD=1.20, scale 1–5).

The self-perceived mathematics ability was measured with one indicator (item). Students were asked to rate, on a 1–5 scale (1= low ability) how well they were able to perform mathematics when compared with an average electrical engineering student. The one-item mathematics scale was used to show construct validity alongside the EMARS scale. These two scales should correlate if they measure similar constructs of self-perceived mathematics abilities. A one-item scale was used to reduce the total number of items in the overall questionnaire.

4.5 Data analysis

The data preparation and analysis were conducted by using SPSS Statistics 18.0 and Amos 18.0. Using box plots and Mahalanobis distance, we observed no univariate or multivariate outliers. The normality was tested with Kolmogorov-Smirnov normality test and by looking at the variables' distributions. The symmetry of the distribution in each variable was examined by dividing the numerical value of skewness with the standard error. The items with values in the range of -2 and 2 were considered to be symmetrical (Cramer, 1997). Fourteen items out of the total 30 original EMARS items were skewed more than 2.0, in absolute value, and were therefore considered to be severely non-normal. The measure of prior performance in mathematics and physics was an average of the student's three pre-engineering mathematics (and physics) courses (scale 1-5). These two grade points averages were also not normally distributed. The distributions of the variables were slightly skewed to the right, meaning that most of the data values were below the mean value. They were, however, included in the analysis. The other dependent and independent variables were normally distributed.

Table 2. The analyses conducted in each study.

Study	Analysis
Study 1: Conceptual and procedural knowledge	Pearson product-moment correlation (*r*)
Study 2: Complex problem exercises	Pearson product-moment correlation (*r*) Stepwise linear regression analysis
Study 3: Alternative conceptions	Frequency distributions Fisher's exact test Analysis of variance (One-Way ANOVA)
Study 4 and 5: Math anxiety	Exploratory factor analysis (EFA) Confirmatory factor analysis (CFA) Pearson product-moment correlation (*r*) Independent sample t-test Analysis of variance (One-Way ANOVA)

The data was found to fit well to linear analysis. The initial scatterplots showed clear linear associations between the independent and dependent variables. The multi-collinearity was checked from the initial correlation matrix and from collinearity diagnostics. There were no indications of problems with multi-collinearity. The analyses used in each study is shown in Table 2.

5. Results

5.1 The overall performance of the students

This section describes students' performance in the complex problem exercises during the course, following the CSEM pre- and post-test results, and finally examining students' performance in the problem-solving exam exercises.

The complex problem exercises

Altogether 111 students returned complex problem exercises during the course. From the total group of students (*N*=133), 17% did not return any of the exercises. Overall, a great majority of the students did take part in problem-solving exercises.

Table 3. Students' performance in complex problem exercises.

Complex problem exercises	*n*	*M* (*SD*)[a]
1. Volume integration	107	8.68 (1.71)
2. Field visualization	65	6.04 (2.79)
3. Image charge	80	7.96 (2.53)
4. Resistance approximation	70	5.64 (3.42)
5. Magnetic field of current loop	66	5.05 (1.96)
Mean	78	6.7 (2.50)
Relevance for learning[b]	101	3.66 (1.04)

Note. Grading scale is 0-10.

[a] The means and standard deviations apply to the returned answers.

[b] The complex problem exercises' relevance for students' learning was judged on 5-point scale (1=not at all relevant, 5=highly relevant).

The first exercise (*n*=107) attracted most answers (see Table 3). From the total group of students that returned complex problem exercises, 96% completed the first exercise. Of note was the difference in the number of returned answers between the exercises 1 and 2. The number decreased by 42, which is 39% fewer returned answers in problem 2. Then, with the third exercise, the number increased again up to 80. This could be explained by the nature of exercise 2, which was not an ordinary mathematical problem, but a slightly complicated visualization exercise. The third problem, being much more traditional, again attracted more answers. By the end of the course, the number of students having returned their answers slowly decreased down to 66 which was 59% of all students and still one more than in the second problem.

Generally, the students succeeded quite well in the complex problem exercises. The means of problems 1 and 3 were notably high, and also the lowest mean in problem 5 was still slightly above half of the maximum. The average of how many homework points students had gained from all five exercises was 48% of the maximum. Nearly one fifth of the students (18%) gained more than 75% of the maximum points.

The first exercise (see Appendix) could be considered fairly easy. It was a purely mathematical integration exercise. The students' mistakes in this problem were mostly made due to carelessness. The most common one was to confuse the radius and the diameter of the sphere with each other. Another common problem was how to formulate the integrated function correctly. Very few students had problems with the integration itself.

The second problem was the visualization problem and it seemed not to attract students, since the number of returned answers was the lowest. The grading of the problem was naturally quite subjective and the students were given points on how well they had managed to visualize the actual fields and potentials but also by the effort it had required them to construct three dimensional models, for example.

The third problem considered the image charge of a sphere. The solution was obtained by a method known as Kelvin inversion. The superposition of the fields of the original point charge and the image charge was computed on the surface of the sphere, and by differentiation, it was supposed to find the radius of the sphere, for which the field had its minimum value. The method of image charge was commonly known and most students succeeded very well in this exercise. Most problems occurred with treating fields as vectors which often was seen as wrong signs in the field terms.

The fourth exercise was to approximate a resistance value. Again, many students succeeded well, but as stated above, the students were divided into two groups, those who understood the idea and got the full points and those who had misunderstood the method or simply did not apply it at all.

The fifth problem consisted of several parts and required a lot of work, including using numerical software. Only a few students had managed to answer all the sub-questions in the problem. Also, many students did not use software in computing or visualizing the results. This exercise had the lowest average points, as most of the students had answered it only partially.

The CSEM test

The overall performance of the engineering students in the CSEM concept test was fairly good. The students' pre-test (*n*=103) score was 57% and post-test (*n*=102) score 67%. The normalized learning gain (*g*), which is defined as the actual average gain divided by the maximum possible gain (%post−%pre)/(100−%pre), was .23. Based on Hake's classification, this is considered to be low-gain (Hake, 1998). In more traditional courses that have low interactive engagement, the average gain varies generally between .15 and .30. There was no significant difference in the performance between men and women prior to the course. On the post-test, however, male students achieved slightly higher scores ($t(101)=3.56$, $p<.01$).

Table 4. The average difficulty (in percent correct), standard deviation in percent (among questions in each area), and average gain of the five conceptual areas of the CSEM.

	Pre-test *n*=103		Post-test *n*=102		Gain
The CSEM area	*f* %	*SD*	*f* %	*SD*	*g*
1. ECF	69	18.4	77	19.7	0.26
2. EFF	60	24.0	66	20.8	0.16
3. EPE	57	16.6	68	13.8	0.25
4. MFF	52	15.6	59	17.2	0.16
5. NL	48	19.8	63	20.5	0.30

Note. The conceptual areas of the CSEM: Electric charge and force (ECF), Electric field and force (EFF), Electric potential and energy (EPE), Magnetic field and force (MFF), and Newton's laws (NL).

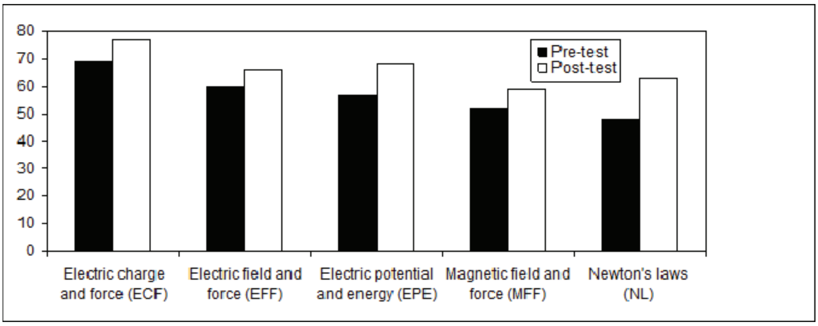

Figure 2. The difficulty (in percent correct) of each conceptual area of the CSEM.

Table 4 and Figure 2 illustrate the average difficulties, corresponding standard deviations and the learning gains of each conceptual area. The least difficult was the area of the electric charge and force for which nearly 70% of the students answered questions for this area correctly prior to instruction. On the post-test, results were as high as 77% correct. The most difficult areas for students were magnetic field and force, and Newton's laws, for which only half of the students answered questions correctly prior to instruction. After instruction, the number of correct answers increased to approximately 60%. The learning gain was the lowest on the areas of electric and magnetic field and force, and the most impact from instruction was in the area of Newton's laws.

The average confidence level of students before the course was 1.97 (SD=0.42) (scale 1-3), which increased after the course. The post-test mean confidence score was 2.33 (SD=0.46). Students' were most confident in the area of the electric charge and force, and least confident in the area of electric potential and energy. Confidence was related to the performance of the CSEM (pre-test: r=.53, p<.01; post-test: r=.70, p<.01). Women were less confident about their answers on the CSEM. The Independent-sample t-test showed a significant difference in confidence means between men and women, both on pre- and post-testing (pre-test: t(90)=3.60, p<.01; post-test: t(85)=3.57, p<.01).

The exam

Altogether 98 students participated in the final exam. The exam consisted of three problem-solving exercises. The fourth exercise was the CSEM post-test, which was also graded. All three problem-solving exercises were graded with a scale 0-10. The first problem was answered by 95 students, with a mean of 5.99 (SD=3.14), the second one by 93 students with a mean of 5.99 (SD=2.69) and the third one by 84 with a mean of 3.83 (SD=3.19).

The first exercise was a straightforward mathematical problem considering vector analysis. More than one third of students (33%) received 9 or 10 points, but contrarily the same amount of students received 3 points or less, the mean being almost exactly 6 points. This indicates that the students' mathematical skills varied a great deal.

The second problem considered electrostatic image charge principle with two original charges. The average score was 6 points, and 69% of the students scored above this. Again, a very notable problem was that many students had difficulties with vectors. Therefore, they were unable to correctly construct the total electric field as a superposition of several fields. It seems that the concepts of electrostatics, for example, the image charge principle and Coulomb's law, were familiar to most students. Instead, the most difficulties in this exercise were mainly due to a lack of mathematical skills.

The task in the third exercise was to compute a superposition of two magnetic field components caused by static electric currents. As in the previous exercise, the solution was very much based on vector calculus. This exercise caused most problems. The mean score was slightly below 4 points and 69% of the students received 4 points or less. As before, the vectors seemed to be the most difficult thing. The students also had problems formulating the expression for the magnetic field.

Considering this exam, it seems that the students were not as familiar with the magnetostatics as they were with the electrostatics. There were also problems with the required mathematics.

5.2 Conceptual and procedural knowledge (Study 1)

The aim of the study was to assess students' conceptual knowledge of electrostatics and magnetostatics and examine how their conceptions change after instruction. The possible relation between students' conceptual and procedural knowledge was also examined.

Measures

The conceptual learning gains were measured by using the Conceptual Survey of Electricity and Magnetism (CSEM) test. The procedural knowledge of students was measured by assessing their performance in the problem-solving exercises in the final exam. In addition to the autumn 2007 pre- and post-test data sets (n=103 and n=102, respectively), we analyzed the data set collected from the autumn 2010 pre-test (n=130). The relationship between conceptual and procedural knowledge was examined only on the autumn 2007 data set. The number of participants with matching CSEM post-test and final exam data was 102. The data were analyzed using frequency distributions and Pearson product-moment correlation.

Results

The overall success of undergraduate engineering students, prior to the course, on the CSEM was 57% and 59% of correct answers in years 2007 and 2010, respectively. The pre-test results indicate that the level of preliminary knowledge of the students was quite equal in both years. The overall results reveal a notable disparity between electricity and magnetism questions. In 2007, the pre-test scores were 62% (electrostatics) and 45% (magnetostatics), and the post-test scores 72% (electrostatics) and 54% (magnetostatics). In 2010, the pre-test scores were 64% (electrostatics) and 45% (magnetostatics). The electrostatic questions were considerably easier for students than the questions relating to magnetostatics. The engineering students performed 17% (2007) and 19% (2010) poorer on the magnetism questions compared to the electricity questions. Furthermore, the learning gain (g) was different in the two topics: on magnetism questions g was only .17 while on electricity questions the gain was .26.

To compare students' conceptual and procedural performance a scatter plot was constructed for the data (see Figure 3). The correlation between conceptual and procedural performance was .49, which, although significant ($p<.01$), was not very high. The CSEM post-test scores explained only 24% of the variance in the exam scores ($r^2=.24$). The first quadrant in Figure 3 contains students that performed well both conceptually and procedurally. More than one third of the participants (33%) were in this group. An equal number of students (33%) were in quadrant 3, which means that they performed poorly in both aspects. The second quadrant contains students that performed well conceptually but poorly procedurally, and the fourth quadrant contains students performing well procedurally, but not well conceptually. It is interesting to note that more students were conceptually strong and procedurally weak (19%) than procedurally strong and conceptually weak (14%).

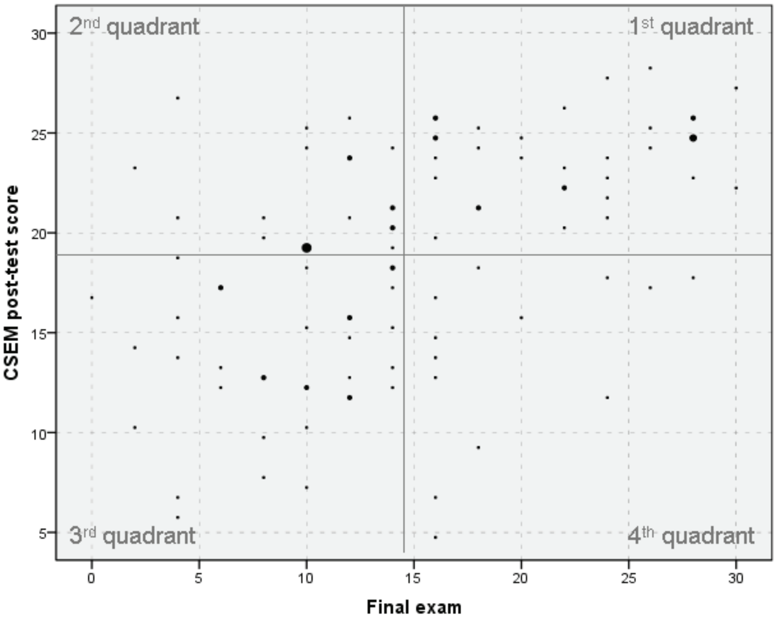

Figure 3. Comparison of scores on the CSEM post-test (scale 1-28) with scores on the final exam (scale 1-30). Figure from Study 1.

Conclusions

The findings suggest that undergraduate engineering students have considerably more difficulties with magnetostatics than with electrostatics. This applies to both conceptual and procedural knowledge. Even though the magnetostatic phenomena are more visible than the electrostatic ones (for example, permanent magnets and compasses), the procedural mathematical treatment of magnetic quantities seems to be more problematic for students.

The results indicate that there is a relation between conceptual and procedural knowledge when learning electro- and magnetostatics. The findings of this study can be said to generally favor the dynamic interaction view that conceptual knowledge is a necessary but not a sufficient condition for procedural knowledge. Nearly one fifth of the students (19%) performed well conceptually, but did not succeed in the final exam. Fewer students (14%) lacked conceptual knowledge but were proficient in procedures and problem-solving. This suggests that some general knowledge of the basic concepts and their relation are needed in order to succeed in complex problem-solving. The findings reveal, however, that in the context of electromagnetics, it is possible to have conceptual knowledge without having procedural skill but not vice versa. As the dynamic interaction view proposes, the conceptual knowledge forms the basis for learning new procedures, but once acquired, procedures develop independently.

As stated in the methods section, the CSEM instrument is somewhat more reliable of measuring conceptual knowledge than is the problem-solving exercises in the exam measuring procedural knowledge. Since the least number of students were placed in the fourth quadrant (high procedural and low conceptual knowledge) suggests that the problem-solving exercises include elements of conceptual knowledge as well. The result shows that it is highly unlikely that a student would succeed in the problem-solving exercises, but perform poorly in the CSEM test, because they both require conceptual knowledge.

5.3 Complex problem exercises and performance (Study 2)

The aim of this study was to examine whether complex problem exercises improve students' procedural and conceptual knowledge of electromagnetics during an introductory field theory course.

Measures

Students solved, as described in section 4, five complex problem exercises during the Field Theory course. The two performance measures (the CSEM and the problem-solving exercises of the final exam) were used in order to assess the impact of the complex problem exercises on students' conceptual and procedural performance.

The relation between complex problem exercises and performance was analyzed by using the Pearson product-moment correlation. The success in the problem-solving exam exercises and the CSEM post-test were predicted using Stepwise linear regression method. Additional cognitive variables, such as the CSEM pre-test score, prior success in mathematics, and prior success in physics were also used as predictors of success.

Results

According to the course feedback, the students felt that the complex problem exercises had been relevant for their learning (*M*=3.66, *SD*=1.04, scale 1 = no relevance, 5 = highly relevant). The performance of students in the problem-solving exam exercises was significantly related to performance in complex problem exercises (r=.49, p<.01). All exercises correlated significantly (p<.01) with the total exam score. The CSEM post-test results, however, were only weakly related to performance in the complex problem exercises (r=.20, p<.05). Furthermore, when the relation was compared between each problem, no significant relationship was found, except in problem 3. The image charge problem had a weak correlation to the CSEM post-test performance (r=.22, p<.05).

Table 5. Summary of Stepwise linear regression analysis for variables predicting students' success in the exam and in the CSEM concept test. Table from Study 2.

Variable	β	R^2
Predicting success in the exam		
CSEM pre-test score	.38**	
Pre-engineering maths[a]	*ns*	
Pre-engineering physics[a]	.31**	
Performance in complex problem exercises	.22*	
		.45
Predicting success in the CSEM post-test		
CSEM pre-test score	.71**	
Pre-engineering maths[a]	*ns*	
Pre-engineering physics[a]	*ns*	
Performance in complex problem exercises	*ns*	
		.50

[a] Performance in maths and physics: mean of three courses (1-5 scale)
**p*<.05. ***p*<.01. *ns* nonsignificant

The linear regression method was used to determine how important a predictor of success the performance in complex problem exercises would be (see Table 5). First, the success in the exam was predicted. All variables except prior performance in mathematics were significant in predicting success in the exam. The model fit well to the data set (p<.01). The variation in the CSEM pre-test score, prior performance in physics, and performance in complex problem exercises (R^2=.45) explained 45% of the variation in students' exam success. The performance in complex problem exercises was as important a predictor of the success in the exam as were prior performance in physics and the CSEM pre-test score.

Next, the success in the CSEM post-test was predicted using previous variables as predictors. Only the CSEM pre-test score significantly explained the variance of the success in the CSEM post-test. The model was statistically significant (p<.01). The CSEM pre-test score explained 50% of the variance in the CSEM post-test variable (R^2=.50). The performance in complex problem exercises did not predict the success in the CSEM post-test.

Conclusions

The results indicate that complex problem exercises do not significantly improve conceptual knowledge of students of electromagnetics. Complex problem exercises, however, increase students' success in the problem-solving exam exercises. The finding suggests that complex problem exercises significantly improve students' procedural knowledge of electromagnetics. The exercises develop students' skills to identify and formulate problems and to carry out procedures appropriately. In addition, practicing complex procedures through problem-solving seems to be a motivating way of learning for engineering students, especially.

5.4 The impact of alternative conceptions on performance (Study 3)

The aim of the study was to investigate the consistency with which Newton's third law concept is used by individual students in different electromagnetic contexts. It was hypothesized that there is a relationship between each of the Newton's third law questions. Students that are choosing one model answer are more likely to apply the same model answer to the other Newton's third law questions as well. We examined whether these possible models are related to conceptual change and overall performance of students.

Measures

In the CSEM, four questions (4, 5, 7, and 24) address the conceptual area of Newton's third law. Newton's third law is an action-reaction law which in the context of the electric force between two point charges means that both charges exert a force on each other, which is equal in magnitude but opposite in direction. Prior studies (Maloney et al. 2001; Planinic 2006) have shown that students fail to apply Newton's third law in electromagnetic situations. Students use an altrnative explanation, called Ohm's Law phenomenological primitive (p-prim). Ohm's Law p-prim is an abstraction from experiences involving an agency, a result, and a resistance: The stronger the agency, the greater the result; the stronger the resistance, the weaker the result. The Ohm's p-prim gets activated by students in circumstances were Ohm's Law is applicable, providing rapid qualitative analysis (diSessa 1983). Instead of applying Newton's third law or Coulomb's law of symmetry, the Ohm's p-prim provides an applicable explanation for students.

In these four Newton's third law questions in the CSEM, some of the distracters activate the Ohm's Law p-prim as well as other incorrect conceptions. Based on model analysis by Bao and Redish (2006), we defined three different *student models* concerning the conceptual knowledge of Newton's third law in the context of electromagnetics:

1. *Null model*: no model
2. *Ohm's p-prim*: the bigger the charge, the bigger the force.
3. *Correct model*: to every action there is an equal and opposite reaction.

For the analysis, students' answers on the four questions relating to Newton's third law were re-coded according to the different models.

In order to study whether students have consistent or partially consistent alternative models when reasoning about Newton's third law principle in the context of electromagnetics, students' answers to four questions relating to Newton's third law were grouped into the following *student model states*. Those students that had given a correct answer to every question were considered to have a *consistent correct model*. Those students that had given correct answers to three questions were considered having a *partially consistent correct model* of Newton's third law. Similarly, students that selected an Ohm's p-prim model answer to three or four questions were grouped into a *p-prim model*. Students that had chosen a null model answer to three or four questions were grouped into a *null model*. The remaining students were grouped into a *mixed model*, since they were using three different conceptual models inconsistently. The relationship between the four Newton's third law questions was examined with the Fisher's exact test. The group mean comparison was conducted using analysis of variance (ANOVA) and pairwise comparisons.

Results

The observed values in Table 6 show that 46% of students were using a consistent correct model and 6% a consistent p-prim model prior to instruction. After the course, the number of students using a consistent correct model increased to 61%, while the consistent p-prim model became almost non-existent (1%). Prior to instruction, 14% of students used a partially consistent correct model, and 12% a partially consistent p-prim model. After instruction, 18% and 9% of students were answering partially consistently, according to the correct and p-prim models, respectively. Before instruction, 20% of students were in a mixed model state, which indicates that this group of students was inconsistent in using their models. After instruction, the number of students in this group decreased to 10%.

Table 6. Observed values (%) for consistent, partially consistent, and mixed student models before (*n*= 103) and after (*n*= 102) instruction. Table from Study 3.

	Consistent model			Partially consistent model			Mixed model
	Null	P-prim	Correct	Null	P-prim	Correct	
Pre-test	1.0	5.8	45.6	1.0	11.7	13.6	20.4
Post-test	0.0	1.0	61.2	1.0	8.7	18.4	9.7

Note. Consistent model: the same model answer in all four questions. Partially consistent model: three out of four questions the same model answers.

Based on Fisher's exact test, our sample provides sufficient evidence to reject the null hypothesis of no relationship between the questions. The result indicates that students are more likely to choose a p-prim model answer consistently in Newton's third law questions. Nearly one fifth of students (18%) before instruction, and 10% after instruction, had a consistent or partially consistent alternate p-prim model of Newton's third law principle in the context of electromagnetics.

The analysis of the frequency distributions show that the students in a correct model state were more likely to answer the four Newton's third law questions correctly also after instruction. The students in a p-prim model state were also more likely to answer the four questions correctly after instruction compared to students in the mixed model state.

The overall performance of students on the CSEM post-test was compared between the three pre-instructional student model states. The One-Way ANOVA analysis showed that the means differed significantly between the three different models ($F_{2,85}$=26.9, p<.001). By definition, students using a correct model performed considerably better on the CSEM post-test, compared to students using a p-prim or a mixed model. Moreover, the mean CSEM post-test score of students using a p-prim model was higher than the score of students using a mixed model. Pairwise comparisons (after the Bonferroni correction) showed that the students in the correct model state differed significantly in conceptual performance from the students in the p-prim ($t(85)$= 2.8, p<.05) and mixed model ($t(85)$= 7.3,

$p<.01$) states. The difference between the p-prim and the mixed models was also significant ($t(85)= 3.1$, $p<.05$). The students using a p-prim model scored on average 4.5 points better on the overall CSEM post-test compared to the students using a mixed model. Furthermore, the students in a correct model state were also more successful in the final exam (problem-solving exercises) compared to the students using the p-prim or the mixed model. The students using the p-prim model succeeded slightly better in the final exam compared to the students using the mixed model, but the difference was insignificant.

Conclusions

The study found a significant relationship between students' responses to the questions of the Newton's third law principle in the context of electromagnetics. Students choosing one alternative p-prim model answer were more likely to answer according to the same p-prim model also in other Newton's third law questions. This result indicates that students' alternative ideas were not fragmented and lacking in consistency. The study also suggests that students applying an alternative p-prim model succeed much better on the overall concept test, compared to students applying a mixed conceptual model. Conceptual change of students in the p-prim model state was much more rapid compared to students in the mixed model state. Students using a p-prim model were more likely to change their conceptual knowledge towards a correct model, compared to students using a mixed model.

5.5 The impact of mathematics anxiety on performance (Studies 4 and 5)

The aim of the study was to investigate the relationship between mathematics anxiety and the performance of engineering students in electromagnetics. It was hypothesized that there is a relationship between mathematics anxiety and performance. Possible influencing relationships such as prior success in mathematics and physics, age, length of studies, and students' self-rated mathematics ability were also assessed.

Measures

Engineering students' mathematics anxiety level was measured with the Electromagnetics Mathematics Anxiety Rating Scale (EMARS) before and after the Static Field Theory course. In total, 118 students participated in the study. During the first lecture, students (n=103) were asked to fill out the EMARS pre-test questionnaire. The EMARS post-test data (n=102) were collected during the final exam. The number of students with matching pre- and post-test data was 88. The two performance measures were used in order to measure the impact of mathematics anxiety against students' performance. The data were analyzed using descriptive statistics, correlation, and analysis of variance (ANOVA). The exam (problem-solving exercises) and CSEM post-test scores were compared in terms of z-scores. The z-score is calculated by dividing the deviation of each score from the mean by the standard deviation of the scores (Kline, 1993).

Results

The mean pre-test EMARS score was 37.09 (SD = 8.03, scale 14-70). The overall anxiety level increased slightly after instruction to 37.96 (SD = 8.03, scale 14-70), but the difference was insignificant, as were the small differences in EMARS scores between men (M_{pre}= 36.76, M_{post}=37.60) and women (M_{pre}=39.90, M_{post}=40.91).

There was a significant decline in performance scores with increasing mathematics anxiety. The relationship was especially strong regarding exam success (problem-solving exercises), which measured procedural knowledge and problem-solving skills in electromagnetics. The decline was less pronounced in the CSEM post-test scores that measured students' conceptual knowledge of electromagnetics. In fact, the students with high mathematics anxiety performed better in the CSEM post-test compared to students with medium mathematics anxiety. Figure 4 compares the exam (problem-solving exercises) and CSEM post-test z-scores. The mean z-score of the high anxiety group was close to average in the CSEM test, but below average in the exam.

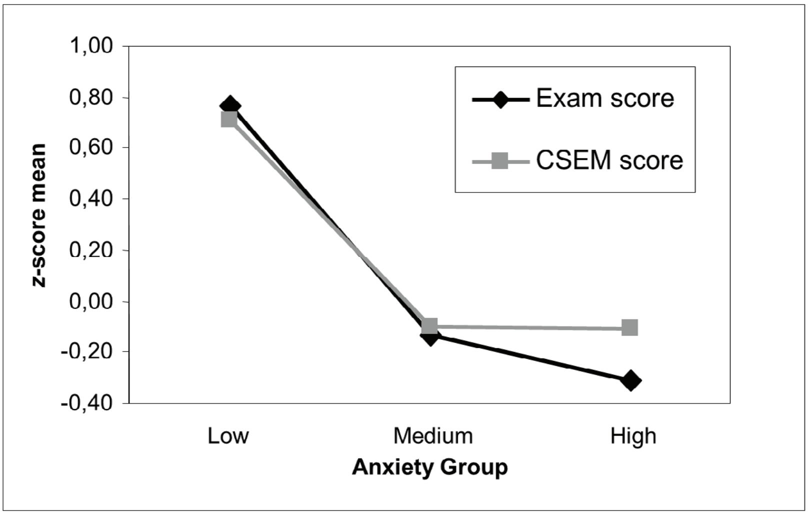

Figure 4. Mean exam and CSEM score (z-score) across anxiety groups. Figure from Study 5.

The original correlation between exam and anxiety (−.37, $p<.01$) remained significant although weaker (−.26, $p<.05$), even after the common variance with prior performance in mathematics was statistically partialled out. In contrast, the original correlation between CSEM post-test and anxiety (−.25, $p<.05$) became nonsignificant (−.18, *ns*) when the common variance with prior performance in mathematics was statistically removed. These findings suggest that the decline in procedural performance in electromagnetics was distinctly related to mathematics anxiety. The variations in conceptual performance, however, were less clearly related to mathematics anxiety.

Conclusions

The results show that mathematics anxiety impacts engineering students' performance in electromagnetics. Students with high mathematics anxiety, however, perform relatively well in the concept test when compared to their performance in procedural problems. The results suggest that a conceptual approach to teaching and learning produces less anxiety among low-achieving students.

6. General discussion

The present study was designed to consider the relationship between procedural and conceptual knowledge, and mathematics anxiety, in the case of electromagnetics. The simultaneous activation view proposes that students make computational errors because mathematical symbols are meaningless to them. Furthermore, symbols fail to take on meaning because they are learned without conceptual knowledge. The dynamic interaction approach, on the other hand, suggests that conceptual knowledge forms a basis on which new procedures are learned. Once learned, procedures develop separately through proceduralization, discrimination, and generalization. Conceptual and procedural knowledge also appear to interact gradually over time rather than simultaneously when students are solving mathematical problems. (Byrnes & Wasik, 1991)

The findings of this thesis generally favor the dynamic interaction view for two reasons. First, Study 1 showed a weak correlation between conceptual knowledge and procedural performance. The CSEM post-test scores explained only 24% of the variance in the exam scores. The findings suggest that in the context of electromagnetics, it is possible to have conceptual knowledge without having procedural, but not vice versa. Some general knowledge of the basic concepts and relations of electromagnetics are needed in order to succeed in problem-solving. This indicates that conceptual knowledge is a necessary but not a sufficient condition for the acquisition of procedures in electromagnetics. Second, Study 2 revealed that prior conceptual knowledge predicted success in the final exam, but developing students' procedural knowledge with complex problem exercises during the field theory course did not significantly enhance students' conceptual knowledge. Hence, in the context of electromagnetics, procedural and conceptual knowledge seem to develop somewhat independently from each other.

Physics education researchers have debated for some time about the conceptual coherence of students' reasoning. The disagreement has been on whether students' common or naïve beliefs form a consistent model or whether the beliefs are merely unstructured pieces of knowledge that need to be corrected (Vosniadou et al. 2008; diSessa 2008). Although Study 3 only focused on a single knowledge element (conception of Newton's third law) the findings can be said to generally favor the consistent alternative conceptions model again for two reasons. First, the study found a significant relation between students' responses to the questions of the Newton's third law principle in the context of electromagnetics. The students choosing one alternative p-prim model answer were more likely to answer according to the same p-prim model also in other Newton's third law questions. This result suggests that students' alternative ideas were not fragmented and lacking in consistency. Second, the students applying an alternative p-prim model succeeded much better on the overall concept test, compared to students who were applying a mixed conceptual model. Conceptual change in students using the p-prim model state was also much more rapid compared to students in the mixed model state. Students using a p-prim model were more likely to change their conceptual knowledge towards a correct model compared to students using a mixed model. According to framework theorists, the presuppositions (such as p-prims) of the explanatory frameworks of students can either facilitate or constrain conceptual change (Vosniadou, 2002). Prior studies show also that students with more structured intuitive knowledge tend to change alternative conceptions more easily (Oliva, 2003). The findings of the current study suggest that the consistent alternative model facilitated conceptual change. Students were not just making mistakes, but were applying theories to explain the physical phenomena. Although the model was not yet scientifically correct, students showed much more developed and conceptually stable reasoning compared to students in a mixed model state.

The present study found a significant relationship between mathematics anxiety and performance in electromagnetics, although the relationship was not completely straightforward. The results indicate that students with high mathematics anxiety perform relatively well in an exam requiring conceptual knowledge when compared to their performance in procedural problems.

The current thesis has important implications for mathematics-heavy disciplines of engineering. The study indicates the need for educational practice to broaden its view of what type of knowledge is valued and assessed in engineering courses. In curriculum design, there could be more emphasis on conceptual knowledge, which triggers less anxiety among low-achieving students. As studies in the context of mathematics and physics have shown, students taught with the conceptual approach perform as well as "procedurally" taught students, or even better (Pesek & Kirshner, 2000; Chappel & Killpatrick, 2003, Mazur, 1997). Furthermore, the conceptual approach encourages students to discuss and reflect on their own ideas and this eventually improves their conceptual reflection and clarification. If the goal in educating future engineers is to increase critical thinking, reasoning, and conceptual understanding, these skills need to be supported in teaching as well as in assessment practices.

The limitation of the current study is that it consisted of only one sample of students and it was conducted at a single institution with a single instructor. Study 1, however, also consisted of a data set from the year 2010. The comparison of the CSEM pre-test scores in years 2007 and 2010 show that the test is stable and consistently produces the same scores under the same conditions. Based on these findings, we could expect the same phenomenon in other electrical engineering disciplines (e.g. circuit analysis, signal processing) that are highly abstract and require the students to use powerful mathematical tools, although this assumption would necessitate future research for verification. Furthermore, since the study was conducted with a correlational research approach, less control was exercised over the independent variables compared to an experimental research approach (with control groups). This is also a limitation of the study, since we cannot suggest any causal relations among variables. Further experimental research is recommended in order to determine possible causalities, for example, between mathematics anxiety and the performance of students of engineering.

Although concept inventories have been widely used especially in the United States over two decades, their usage is fairly new at the Aalto University School of Electrical Engineering. The CSEM concept test has been used in introductory electromagnetic courses since 2007 and the test has provided useful diagnostic information of students' conceptual barriers. The reviewers of Study 3 for the journal *Research in Science Education* have shown an interest in the classification of students' alternative p-prim models in the CSEM concept test. On the other hand, they have argued that four multiple-choice questions is not a sufficient number of questions to make inferences about the consistency of students' answers and have recommended adding more questions to the CSEM test. The present study suggests, however, that there is sufficient evidence to conclude that this type of classification is suitable for detecting students' consistency for applying alternative models. One of the great advantages of the general concept inventories is that they provide useful, reliable, and comparable information of students' common conceptions, the effect of instruction, and the consistency of student models. We would strongly encourage instructors and teachers in engineering education to introduce the concept inventories for instructional and assessment practices.

In educational research, it is clearly challenging to try to design a study where all potentially affecting cognitive and affective factors can be identified and their influence controlled. For example, the course under study included also a project work but its impact was not examined due to the fact that it was a joint group effort. All students in the group received the same mark and hence individual students' contributions were not identified. Furthermore, surveys and statistical analysis alone cannot provide sufficient knowledge about how students learn and how we should develop engineering education. Some abilities, such as critical thinking skills or effective problem-solving, can be assessed also very effectively by qualitative methods. Nevertheless, hopefully the results of the present thesis will contribute to research aiming to form a deeper understanding of engineering students' learning behaviors and outcomes.

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Appendix

The complex problem exercises

1) Archeologists discovered a strange metal object: a 10-cm diameter hollow sphere. The shell thickness was only one centimeter. The material turned out to be a metallic mixture with a given percentage of gold: on the inner surface the share of gold was 1 percent in weight and this concentration of gold decreased linearly with increasing radius in such a manner that on the outer surface of the sphere. How much pure gold did the object contain, given that the density of the material was 12000 kg/m^3? How much would there be gold if the concentration of gold were uniformly 0.5% throughout the shell?

2) The most efficient and dense way to convey quantitative information about scalar and vector fields is probably the use of field equations and formulas. That, however, may not be the most visual and illustrative. In this exercise, consider the field caused by four point charges in free space. The charges are located, according to the figure, in the origin (+2*Q*), in the position of one meter on the *x* axis (-2*Q*), at one meter on the *y* axis (-*Q*), and one meter on the *z* axis (+*Q*). (See Fig. 1)

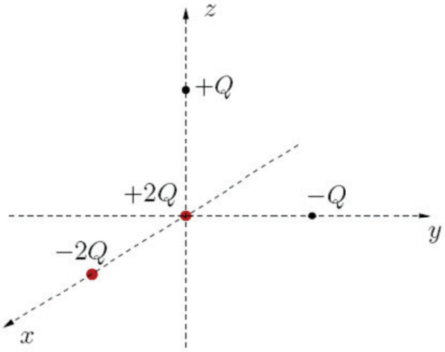

Fig. 1. Positions of charges in problem 2.

Illustrate the potential and field distributions due to the charges as instructively as possible. Remember that vectors have both magnitude and direction. Consider the situation both far away from the charges and also in close range (scale of meters). All instruments allowed, anything goes (colors, pottering, three-dimensional and living models...) Evaluation will be based on the efficiency of the visualization and its correspondence with the reality.

3) A point charge Q is located in the vicinity of a grounded conducting sphere with a distance of one meter from the center of the sphere. The effect of the charge is that on the surface of the sphere, an electric field is created. This field is perpendicular to the surface. Where is this surface electric field at its maximum? This maximum field $E_{\max}$ obviously depends on the radius of the sphere a. Find the value of a for which $E_{\max}$ is the smallest. (See Fig.2)

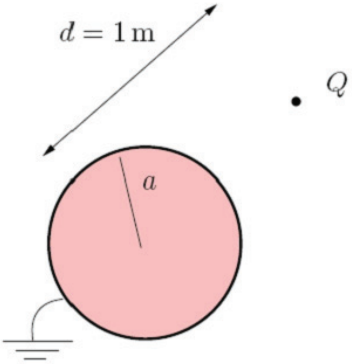

Fig. 2. Geometry in problem 3.

4) Enclosed is a cross section of a twin conductor with rectangular grounded shield. The material between the conductors is not totally insulating; it has a small conductivity of σ = 0.01 S/m. Hence there is leakage current in the transversal plane. How many ohms is the leakage resistance of such a conductor whose length is two meters in the longitudinal direction? To calculate the resistance you probably need to solve (at least approximately) the distribution of the electric potential in the transverse plane. Method is free (graphical drawing and mapping, computer, experimental measurement, analytical-based).

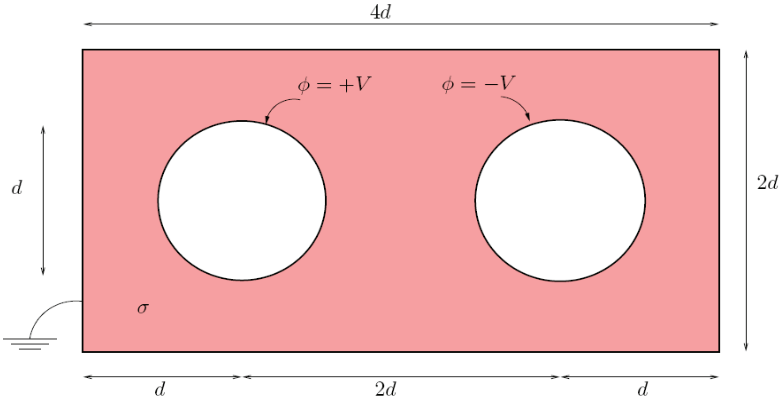

Fig. 3. Geometry in problem 4.

5) A steady current I flows in a circular loop with a radius $a = 1$ m. Let us analyze the magnetic field due to this current on two axes:
   - on the symmetry axis of the loop (z axis)
   - on a transversal axis parallel to the y axis ($x = 0, z = a/3$)

   From far away the loop is "small" and we can approximate it by a magnetic dipole. Calculate the magnetic flux density (direction and amplitude) along these two lines using the dipole approximation. Solve the problem also exactly. Calculate the amplitude and direction angle on both axes under consideration. Plot the curves in the domains $-10a < z < 10a$, $-10a < y < 10a$. (Note that the amplitude of the dipole approximation is infinite at the origin; therefore if you include the approximation in your figure, be careful that the singularity does not spoil your figure). How far from the loop one needs to go in order that the amplitude of the magnetic flux with the dipole approximation is correct with accuracy better than one percent?

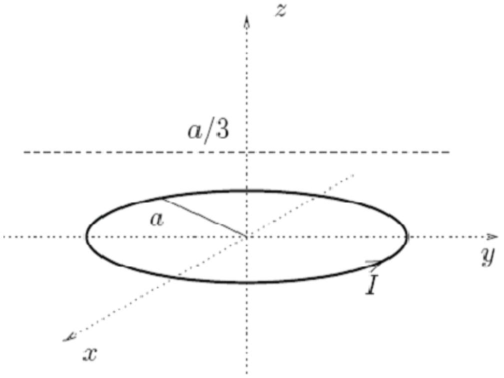

Fig. 4. Orientation of the loop in problem 5.

The problem-solving exam exercises

1) Let us define a vector function using the spherical coordinate system (r,θ,φ) as follows:

$$\mathbf{f(r)} = \mathbf{u}_r \frac{\cos^2 \varphi}{r^3}$$

Let the domain V be the volume between two origocentric spherical surfaces with radii a and b, and S be the surface of this volume. Let us define the directed surface element $d\mathbf{S}$ in such a way that it points out of the volume V. Hence on the inner surface it points towards the origin.

   a) Calculate $\oint_S \mathbf{f(r)} \cdot d\mathbf{S}$

   b) Calculate $\int_V \nabla \cdot \mathbf{f(r)} dV$

   c) Check the validity of the Gauss' law (the divergence theorem) in this case.

2) Two point charges Q_1 and Q_2 are located on a height of $a/2$ over a conducting plane. The distance between the charges is a. The charges have the same sign but a different magnitude: $Q_2 = 2Q_1$. The charges experience forces in this situation. Are the forces equal? If not, which of the point charges experiences a stronger force? How much stronger? Which direction does the force acting on charge Q_1 point, and in which direction does the force on Q_2 point? Express the directions in terms of the angle φ in the xy plane.

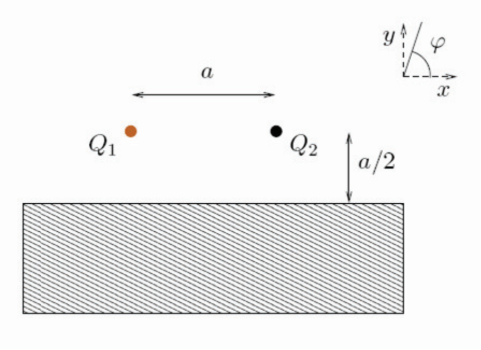

Fig. 5. Positions of the charges in problem 2.

3) Two long straight current-carrying wires are located in free space: one along the z axis through the xy plane point $(-b,0)$, and another parallel to y axis on the point $(b,0)$ of the xz plane. Calculate the absolute value of the magnetic field caused by these currents, everywhere along the y axis. At which point on the y axis is the field strongest? What is the direction of the field there?

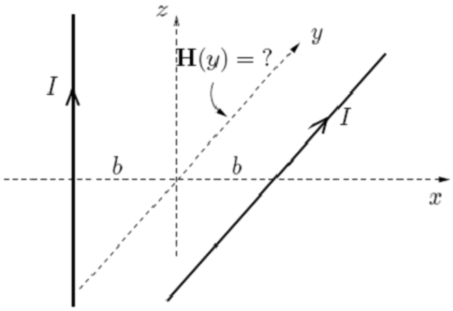

Fig. 5. Positions of the currents in problem 3.

Mathematical proficiency is an important predictor of engineering success. However, the change of the demographics of engineering students has led to larger percentage of students with weak mathematics skills. Furthermore, electromagnetics courses are perceived as abstract and irrelevant. Students struggle with required mathematics and have been shown to have motivational difficulties when studying the subject. Vast amount of research in engineering education has been conducted on the development of conceptual knowledge, but rather little is known about procedural knowledge, and especially how conceptual and procedural knowledge alternate and contribute to the development of expertise. This thesis examined engineering students' conceptual and procedural knowledge, as well as mathematics anxiety that all relate to proficiency in electromagnetics. The findings suggest that there is clearly a need to broaden the view of what types of knowledge are valued and assessed in engineering courses.

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