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Markku Saarelainen

Teaching and Learning of Electric and Magnetic Fields at the University Level

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Author's address: Department of applied physics
University of Eastern Finland
Yliopistonranta 1
P.O. Box 1627
FI-70211 Kuopio, Finland
E-mail: markku.saarelainenuef.fi

Supervisors: Docent Pekka Hirvonen, Ph.D.
Department of Physics and Mathematics
University of Eastern Finland

Prof. Ari Laaksonen, Ph.D.
Department of applied physics
University of Eastern Finland

Reviewers: Prof. Jukka Maalampi, Ph.D.
Department of Physics
University of Jyväskylä

Docent Kalevi Kokko, Ph.D.
Department of Physics
University of Turku

Opponent: Docent Ismo Koponen, Ph.D.
Department of Physics
University of Helsinki

ABSTRACT

The goals of this study are to improve the teaching and learning of electro- and magnetostatics at the university level. This study has four parts: evaluating the students' prior knowledge in the subject area, identifying obstacles to learning, and developing and evaluating teaching strategies that result in good student performance.

Successful learning of electro- and magnetostatics and Gauss's, Lorenz's and the Biot-Savart laws depends on understanding the concept of electric and magnetic fields. The kernel of electromagnetic theory, i.e. Maxwell's four equations, is highly abstract, and the equations are frequently misunderstood.

Previous studies have revealed several learning problems related to electro- and magnetostatics. One is the concept of a vector field. Similar problems were found in this study, too. The students participating in a course on electromagnetics in Kuopio in 2004-2009 were given a test to evaluate their background knowledge and were interviewed in order for the instructor to gain a deeper understanding of their prior knowledge. The analysis of the pre-conceptions revealed that the students were not capable of applying vector representations of electric fields even if they successfully treated forces as vectors. For the students, force is a more concrete concept than field. Regarding magnetism, the students confused it with electric field and force. Furthermore, understanding the use and the basis of the specific Right -hand rules for the magnetic field and force was challenging for the students since they did not possess a proper theoretical foundation for those rules.

By eliciting information about students' thinking, it is possible to address the most common obstacles to learning. Having a correct concept of vector field was found to be the key for successful learning for the majority of the students. This finding is in accordance with previous results showing that students faced difficulties when changing their thinking from the Newtonian model (of force acting on a physical object from a distance) to the Maxwellian model (of the idea of the field being the media of the interaction).

In order to devise more effective teaching, we applied the strategy of educational reconstruction. Based on the findings concerning students' conceptions, and analysing the physics content to be taught, new teaching sequences were developed. The sequences consisted of novel lectures with multi-step tasks where they could apply their newly acquired knowledge. Student learning was monitored by using post tests and by analysing final exams. The results indicated that the students adopted vector-related reasoning.

This study provides a precise view of the students' initial concepts of the electric and magnetic fields. It also demonstrates how a fuller understanding of the field concept can be achieved and how this affects instruction.

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Kuopio, November 2011

Markku Saarelainen

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original articles, which are referred to by the Roman numerals I-V

I Saarelainen M, Laaksonen A and Hirvonen P E. Students' initial knowledge of electric and magnetic fields - more profound explanations and reasoning models for undesired conceptions. *European Journal of Physics 28: 51-60, 2007*

II Saarelainen M, Laaksonen A and Hirvonen P E. Students' conceptions and reasoning models of the electric force and field related questions in the interviewed CSEM test. E. Van den Berg, A.L. Ellermeijer, O. Slooten (Eds.), *Modelling in physics and physics education*, 1051. Amsterdam: AMSTEL Institute, University of Amsterdam. 2008.

III Saarelainen M, Hirvonen P E. Designing a teaching sequence for electrostatics at undergraduate level by using educational reconstruction. *Latin American Journal of Physics Education 3(3), 2009.*

IV Saarelainen M, Asikainen M A and Hirvonen P E. Developing instruction in magnetostatics at undergraduate level. I. Undergraduate students' initial knowledge of magnetic field and magnetic force. *Latin American Journal of Physics Education*. Submitted for publication.

V Saarelainen M, Asikainen M A and Hirvonen P E. Developing instruction in magnetostatics at undergraduate level. II. Multistep tasks as an instructional tool developed using educational reconstruction. *Latin American Journal of Physics Education*. Submitted for publication.

AUTHOR’S CONTRIBUTION

The author of this thesis performed all the planning of the study structure in co-operation with his supervisor P. E. Hirvonen. The author performed the data acquisition and analysis in each of the articles I-V. The author wrote articles I and II after receiving comments and suggestions from co-authors P. E. Hirvonen and A. Laaksonen. The author was also responsible for writing article III, after receiving comments from P. E. Hirvonen, and articles IV-V, after receiving comments from P. E. Hirvonen and M. A. Asikainen. The author was responsible for carrying out the instructional approaches found in articles III and V. The five articles I-V will not be used in any other dissertation.

Contents

ORIGINAL PUBLICATIONS

1 Introduction

1.1 BACKGROUND AND MOTIVATION

Electromagnetic field theory forms an essential basis in the physics curriculum and in the physicist's professional competence. It is well known that understanding the basic theory of Maxwell's electromagnetism is a prerequisite for research work in many areas of physics. However, this domain of physics appears to be challenging and confusing, according to the students' feedback. These two points initiated this research project in 2004 at the University of Kuopio (University of Eastern Finland from 2010.)

This research project covers the basic course on electromagnetics during 2004-2009. Around 200 students participated to the course in this time. The course was held annually and the majority of the students who participated in the course were physics majors. The students graduate with degrees in medical physics/engineering or environmental physics/engineering. These two fields of study are developing rapidly due to the demand for more cost-effective diagnosis and treatment in health care as a result of the aging population in the industrialized countries, and due to growing worldwide individual, economic and political interest in environmental concerns as the climate changes. Furthermore, both disciplines are based on a profound theoretical knowledge in physics, together with highly sophisticated methods of computational sciences. At the same time, research on science education has produced information concerning the problems and solutions of learning and teaching. There is growing awareness of the problems and interest in improving both learning and teaching at the university level. The benefits of understanding the learning process and the ways of improving the instruction are increasingly being taken into consideration by instructors. Instructors are encouraged to support their teaching with material such as textbooks, instructor manuals and visual and computer-based aids. The instructors' resource materials contain detailed information on how the research findings in education have been taken into consideration (Young & Freedman, 2008). The quality of teaching has also emerged as one of the topics in discussion of the competitiveness of universities.

A major challenge is bridging the gap between secondary level science education and university level, and the gap between what we teach and what is learned. The basic problem in teaching at the undergraduate level is that, in general, the abstract formulation of physics is a result of theoretical evolution in physics and thus difficult to comprehend for the majority of the students (Hestenes, 1987). This is also the case with electromagnetism. Maxwell's equations, for example, are presented in a compact integral form in a vacuum in the first year course on electromagnetics. In the subsequent courses on electromagnetic field theory there is need for compressing the formalism even more including more sophisticated mathematical tools. However, the basic phenomena and principles in electromagnetics are still the starting point, and a high degree of abstraction or computational manipulation does not eliminate the requirement for conceptual understanding of physics.

An introductory electromagnetics course generally covers the domain of Maxwell's equations in integral form in addition to the basic theory of electric circuits and electromagnetic waves. Learning Gauss's law involves understanding its relationship to the integral calculus of vector fields and their physical interpretation, which is also the case with the other Maxwell equations. Thus, the concept of an electric field plays a key role in understanding Gauss's law, and thus also electric potential, capacitance, and current. Furthermore, the concept of magnetic field forms the basis for understanding Ampere's law, electromagnetic induction and magnetic materials.

Hence, the motivation for this research project was the notion that learning the scientific field concepts would serve the students as an explanatory interlinking subject for the majority of the topics on electromagnetics. These points concern the whole curriculum and the specific topics, so more research here is clearly called for.

One aim of research in science education is to provide development in research-based learning-teaching sequences in practice (Meheut & Psillos, 2004) (Kelley, 2003). The present study attempts to do this by following a social constructivist point of view in designing and evaluating teaching sequences (Leach & Scott, 2003).

1.2 REVIEW OF PREVIOUS RESEARCH

Electricity and magnetism is a vast area in physics and it is subdivided into several branches in science and technology. Several iterations and approaches are applied in education at different school levels. In the level closest to the domain of this research, i.e. from upper high school to pre-instructional undergraduate level, there is a large group of studies that focus on general electromagnetism, electrostatics, electrodynamics, and magnetism. The ones most closely related to this study are studies which focus on the electric and magnetic field concepts.

1.2.1 Electrostatics

The electromagnetics course at university generally covers the domain of the integrally formed Maxwell's equations in addition to the basic theory of electric circuits and electromagnetic waves. However, most studies on learning difficulties in electricity have focused on upper secondary school students and their understanding of simple circuits

(Cohen, Eylon, & Ganiel, 1983)(Duit & von Rhöneck, 1997) (McDermott & Schaffer, 1992)(part I) (McDermott & Schaffer, 1992)(part II)(Salomon F Itza Ortiz, 2004). Indeed, less research has been done at the university level, especially concerning the linking of electrostatic concepts with learning difficulties in circuits, potential and capacitance (Jimenez & Duran, 1998)(Mita & Boufaida, 1999)(Parker, 2002)(Hirvonen, 2007).

A previous study on field-related electrostatic concepts showed that the students have difficulties progressing from the force concept to the theoretically superior field concept (Furio & Guisasola, 1998)(Yeung & Law, 2001).

The mathematical formulation of the electric and gravitational field and force resemble each other to some extent. In the case of mechanics, the gravitational field is seldom treated before force when teaching the basic concepts, e.g. projectile motion. Mechanical forces and their consequences in kinematics and statics are introduced in detail. Hence, it is not surprising that in electrostatics students use the Newtonian action at a distance model and this leads to one central learning difficulty regarding the electric field: there is no differentiation between field intensity and electric force (Furio & Guisasola, 1998). Nevertheless, learning the electric force concept is important since the field concept is built upon it. However, the force concept is so strongly ingrained in students' thinking that advancing to the next level, the field concept, is challenging.

Learning the concepts of electric field involves many representations. Mathematical formulation is certainly the aim of the instruction, but it cannot be reached without describing the field and field-related concepts in more concrete ways. To describe, or visualise, the field around a charge distribution, an instructor can use either field line representation or vector field representation (Chabay R. , 2002). The graphical representation is actually an image or interpretation of the field that can be expressed in mathematical form. Thus the use of the concepts and understanding of the graphical representation reflect our understanding of the essence of electrostatics (Herrmann & Hauptmann, 2000). However, as with many models in physics the field line representation has its advantages and disadvantages. Students have alternative conceptions and reasoning models concerning the electric field lines as an essential presentation of the electric field (Törnkvist, 1993). The field line is understood as an isolated entity instead of a set of curves representing the vector electric field property of space. Furthermore, the students fail in explaining the fields inside an insulator in two ways: the insulator is said to prevent the electric field from "traveling" through the media, and the electric field cannot exist if the charges inside the insulator do not move (Viennot & Rainson, 1992). The field line representation is taken too literally by giving the lines attributes, as the lines are material entities that can play different roles in the transmission of electrical effects. The lines are considered pathways that the charges follow between the electrostatic sources and the drain, in addition to the interpretation of the line as a line of force. A similar kind of travelling feature of a field line is mentioned in Pocovis' findings and in Viennot's findings (Pocovi M. , 2007). This idea of "electricity" travelling through space via the field lines is quite interesting. For example, the expression "the electric flux through a surface" is rather problematic when discussing electrostatics. The students are tempted to use a mechanical flow analogue in the case of the flux. Alternative concepts and reasoning models exist and they have to be taken into consideration when designing instruction. If used correctly, and knowing the limitations, the field line representation is useful, and can be fast and easy to use. However, using field line representation without really understanding the respective field vectors is meaningless, like using any memorised rule blindly.

Students seem to understand the Coulombian electric force as a vector in the cases of a simple arrangement of punctual charges. Problems arise, however, when the electric field vector is introduced to describe an arbitrary empty point in space in the proximity of punctual or continuous charge distribution (Viennot & Rainson, 1992)(Törnkvist, 1993) (Saarelainen, Laaksonen, & Hirvonen, 2006) (Saarelainen, Hirvonen, & Laaksonen, 2007)(Melzer, 2003). This confusion of electric field lines and the general behavior of the static field as a spatial vector field was one reason for including in this study a revised approach putting more effort on a correct understanding of electric field.

1.2.2 Magnetostatics

Previous studies demonstrate that students have difficulty in using relationships and models which are specific to magnetic phenomena. There are various examples where we can detect the presence of electricity indirectly through our senses, e.g. electric shock, electric sparks, electrostatic repulsion and attraction. But this is not the case with magnetism: we cannot feel magnetism in the same way. Thus the initial explanations and reasoning concerning magnetic phenomena are often a result of using analogies from our experiences in similar cases, e.g. gravity, feeling repulsion or attraction as a force, (Bradamante & Viennot, 2007).

In a study concerning undergraduate students' understanding of magnetic fields and interactions, Guisasola (Guisasola J. , 2004) presents several findings that imply that the students tend to explain magnetic phenomena by misusing analogues to electrical ones. According to Guisasola, the source of a magnetic field is understood to be caused by an electric charge, either in movement or at rest, and magnets are considered to be charged bodies. Thus the concepts of electric and magnetic fields are misunderstood, leading to the interpretation whereby magnetic interactions are explained using Coulombian force.

These issues are associated with problem solving and mathematical formalism using vectors and integral calculus with physical descriptions of magnetic field and flux (Bagno &

Eylon, 1997). The difficulties arise in using this formalism in elementary situations (Albe & Venturini, 2001). As found in many inquiries, the mathematics is seen as almost entirely procedural, which means that the physical relation is understood as a calculus operation (Dunn & Barnabel, 2000).

Having a correct understanding of the three-dimensional field associated with the mathematical formalism is essential in studying magnetic field and force. Indeed, Saglam and Millar emphasize the need to develop teaching strategies that help students to visualize magnetic field patterns and effects (Saglam & Millar, 2006). The visualization of 3D electric and magnetic fields and EM waves has become possible and easy to use in education. Computer-based simulations and measurements are applied because students have difficulty in conceptualizing and visualizing the physical concepts, specifically phenomena related to the electromagnetic field (Dori & Belcher, 2005) (Martinez-Jimenez & Pontes, 2001). Besides the use of the vector cross product in the Biot-Savart law, alternative approaches have been reported, including the use of simplified geometrical substitutes for teaching the magnetostatics in case of highly symmetrical or planar current distributions (Miranda, 2000)(Grivich & Jackson, 2000). These approaches are examples of trying to make some problem or a set of examples more accessible by giving alternative methods for the required computation or visualization.

In summary, we find that in magnetostatics the problems arise in connecting the source of the magnetic field and the force to the interactions and in connecting the vector cross production within the relations to the visualizations. The previous studies in this domain cover the basic student performance and address some relevant learning difficulties. However, many questions concerning the reasons for the difficulties remain unanswered, and there is a need for suggestions for overcoming these difficulties by improving the instruction. This was one of the starting points for this study.

1.3 OBJECTIVES AND SCOPE

This research project aims to develop and evaluate innovative and effective instruction for the basic course on electromagnetics. More specifically, it focuses on the concepts of electric and magnetic fields and forces, which are the foundation for understanding the field-related theory of electromagnetism. The topic of field and force was chosen on the basis of the students' performance in the pre-tests, discussions during the lectures, and the instructor's observations. The main aim of the course is to give students an understanding of Maxwell's equations and their practical applications in theory formation and in problem solving. Maxwell's theory is the new topic to be learned, but the course builds on the students' existing knowledge base. Therefore, it seemed worthwhile to gain information on the students' understanding of the topics in the domain and to then start with the basic building blocks – the concepts of electric and magnetic fields and forces. The concepts of fields are meant to guide the students' understanding of the electromagnetic phenomena in the same way as an explanatory model. On one hand, learning the field model constitutes the first steps in understanding the principles of electromagnetics. On the other hand, the field model gives a solid foundation to understanding more sophisticated theory in electromagnetics and the myriad types of applications and instruments that are based on the theory.

1.4 RESEARCH APPROACH

The development and evaluation of the instruction was carried out following the method of Educational Reconstruction (Duit R. , 2000)(Duit R. , 2007)(Duit R. , 1995)(Duit, Komorek, & Wilbers, 1997). This approach is described in more detail in the next chapter. The method provides the tools for connecting the learning difficulties to be addressed, the analysis of the content, and the teacher's perspective on the effectiveness of the instruction. Furthermore, it allows a certain degree of freedom when acquiring the data concerning the students' initial knowledge. There is also flexibility in the practical implementation of the content. By encouraging the interplay between the analysis of content structure, research on teaching and learning, and the development and evaluation of instruction, the method follows the traditions of the constructivist view of learning. However, this is not a matter of blindly following a theoretical framework in education, but a flexible construction with which the teacher can connect the science view and the research findings concerning students' preconceptions. The approach includes various methods of inquiry. In the present study, the students' preconceptions were explored by written tests, final exams, and semi-structured interviews. The fine grain analysis of the physics content structure was based on the existing instructional material influenced by the results of the students' preconceptions and by the instructor's views and experience in most cases, the textbook or workbook assignments that were being used were consistent with the instructional approach used in this study. The material preparation focused on altering and focusing the existing tasks based on the idea of the gradually increasing difficulty, i.e. the steps which the students were expected to take towards the desired learning objectives.

1.5 RESEARCH PROCESS AND RESEARCH REPORT STRUCTURE

This research project consists of iterative sequences of inquiring into the students' preconceptions, developing and implementing the instructional approach, and evaluating the teaching-learning process. The project started at the University of Kuopio in 2004, when all the participated students were tested and subsets of them were interviewed at the beginning of the course. The aim of that inquiry was to map the most frequent issues that seemed to hinder successful learning of electromagnetics in general. There were two main findings: the students had poor understanding of the field concept in both electro- and magnetostatics, and of vector concepts in referring relations in electric and magnetic field and forces. The research was carried out in two cycles, one concerning the electric field and force, and the other concerning the magnetic field and force. In both cases detailed pre-instructional testing and interview sequences were carried out. The cycles continued with the development of instruction and its evaluation.

The first chapter of this thesis explains the background and motivation for the research. The second chapter presents the theoretical framework. The third chapter focuses on the method used and the fourth on the specific issues of the teaching sequences of the electromagnetic theory on which this research is focused. Chapter 5 summarizes the findings of the studies. The final chapter is a summary of the theoretical and practical implications of this research project together with the discussion of trustworthiness.

2 Theoretical framework

Indeed, educational reconstruction involves rearranging and restructuring the teaching sequence. The content of the sequences is based on the students' conceptions and views on learning. In this study I was committed to both the constructivist paradigm that defines and guides the way of approaching inquiry, and the constructivist view of learning as a theoretical approach to the issues of teaching and learning. The constructivist view of learning does not give any direct instructions on how the teaching should be carried out. This study was not about the constructivist view of learning itself, but I was influenced by it and I applied it in the inquiry and instruction. Figure 1 shows the theoretical aspects of the inquiry.

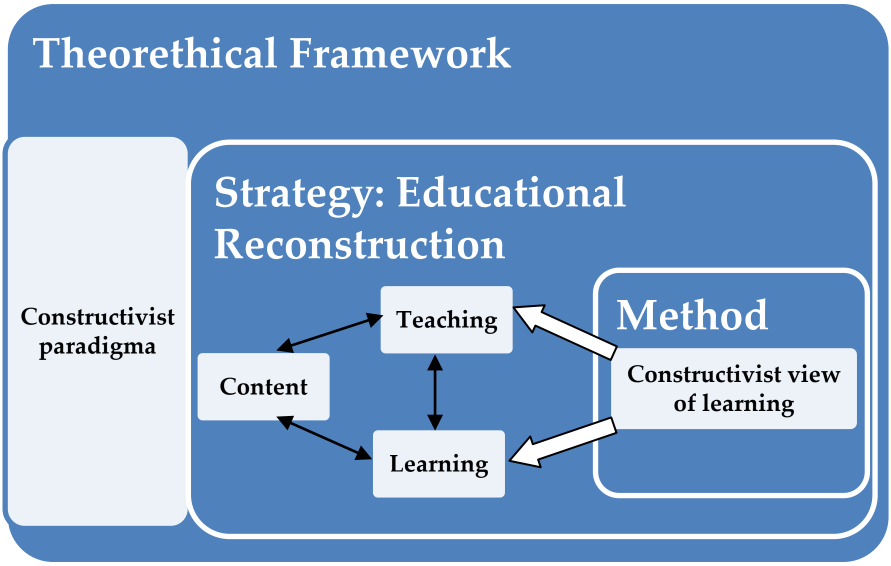


Figure 1. *Theoretical aspects of the inquiry.*

The constructivist paradigm sets the frames within which the inquiry is carried out. Educational reconstruction is a strategy with which the inquiry and the teaching-learning process can be monitored. The constructivist view of learning influences the teaching and learning inquiry and instructional intervention.

2.1 THE PARADIGM

Research in physics and in physics education attempts to answer questions about knowledge and how one obtains valid knowledge. However, there are different ways of answering these questions. The process of inquiry involves scientific methods, which in turn depend on the scientific community for agreement on what constitutes a valid approach to knowledge acquisition. In order to arrive at answers to these questions concerning knowledge and their validity, we must determine how we comprehend the objects and actions under inquiry, i.e. the paradigm we shall adopt. The objectives of the research determine the paradigm.(Husen, 1988)

The paradigm that guides scientific disciplines can be characterized by answers to *ontological, epistemological,* and *methodological* questions (Guba, The alternative paradigm dialog, 1990). According to Guba, the questions can be expressed as follows:

1) *Ontological*: What is the nature of reality?
2) *Epistemological*: What is the nature of the relationship between the inquirer and the knowable?
3) *Methodological*: How should the inquirer go about finding knowledge?

The constructivist paradigm takes into consideration the human interpretation of the external world. Furthermore, the nature of reality is constructed by individuals and mediated by social resources. The inquirer and inquired into are interconnected and the outcome is a changed world rather than simply a described one. In addition, the world is in the minds of constructors as a result of the reconstruction process (Guba, The alternative paradigm dialog, 1990). Hence, the clear border between the ontological and the epistemological aspects in constructivism vanish and are replaced by an active relationship between the spectator and the play.

The following section discusses the view of learning in this study. Consequently, the subject to be taught – physics- has influenced to the choice of the educational reconstruction method. The study includes both the analysis of the physics content and the view of learning.

2.2 VIEW OF THE RESEARCH DOMAIN AND LEARNING

The outcomes of research in physics education have influenced the development of physics curricula at the undergraduate level. Emphasis on the responsibility for learning has moved gradually from the lecturer to the student, in tune with the constructivist view of learning. Examples of curricula that promote students' active participation in the learning process can be found in "Matter & Interactions" (Chabay R. , 2002) , "Tutorials in introductory physics" (McDermott & Shaffer, 2002)"Physics by inquiry" (McDermott, Shaffer, & Constantinou, 2000) and "Tools for scientific thinking" (Thornton, 1987). In these studies, as in the present one, the instructors were provided with materials by the textbook publishers that supported the efforts of activating the students and engaging them in discussions. The students were asked to make predictions, observe, explain, and discuss the outcomes with peers during the instructional interventions: these strategies were based on the direct or modified examples found in the "student workbook" (Knight, 2004). The constructivist view of learning is being used when the teaching is based on feedback from the students' thinking. Instructors apply and evaluate instructional approaches based on this discourse (Redish E. , Implications of cognitive studies for teaching physics, 1994). The students' conceptions are seen as a resource; not only as a set of misconceptions that have to be corrected, but also as items that can be used in redesigning the instruction (Hammer D. , 2000). The students' preconceptions and reasoning models in electricity and magnetism provide a starting point in developing more effective teaching. Thus, in this study I have taken into consideration the context of the topics in order to attach and modify the models the students possess to the physical content, the rules and interpretations. This leads to the manipulation or change of the models so that they are in accordance with the science model, or with the aims of the teaching. An important outcome of the instruction would be for the students to be able to answer the questions of "*what* I know, *how* I think, and *when* and *why* to apply knowledge (Furio & Guisasola, 2003)(Glaser R. , 1984). This metaconceptual awareness can be regarded as a part of individually variable ways of learning that also have to be taken into account (Asikainen & Hirvonen, 2009). These issues that form the core of the view of learning are discussed in the next section.

2.2.1 Constructivism

Constructivism is based on the concept of the learner as an active revisor of information, and the information itself is seen as a dynamic construct (Bereiter, 1994). According to the constructivist view, knowledge cannot be transferred directly from the instructor to the student. The student has to construct the structures of the knowledge for himself/herself during the learning process. The student interprets the information according to his/her earlier knowledge base and experience. Furthermore, the context and the physical and social framework affect the developing construction. The key concepts of the constructivist concept of learning are active thinking, skills in processing information, and metaconceptual awareness. (von Wright & Rauste-von Wright, 1994)(Steffe & Gale, 1995).

According to the constructivist concept, knowledge is an inwardly congruent belief that is viable and works in practice. Furthermore, this knowledge is accepted and shared by the knower and a (scientific) social group. This also includes the idea that non-objective reality consists of the information, empirical observations, and skills that are relevant in the organized knowledge structure (Lave & Wegner, 1991). Here, we can consider the physics culture and society as a frame of reference for the knowledge structure. According to the sociocognitive view of constructivism (social constructivism), individuals are responsible for constructing knowledge, while at the same time social interaction with other members of the group is essential. The other learners, in discussions, give alternative ideas and activate reasoning. This affects the students' thinking when they are forming their own ideas (Brown, Metz, & Campione, 1996).

The community of learners and the community of science resemble each other in this respect; the focus shifts from individuals to the members of community (Posner & Strike, 1982). Thus, this also promotes the importance of the social aspects in the learning environment, i.e. the issues of context, change and variability in understanding concepts in science. As explained in more detail in the following chapters, the principles are not ″theorems" or "laws of cognitive science" and they should be seen as an aid in helping teachers refocus on the learning process. When considering the learning process in the light of the principles, it does not mean that the focus of teaching shifts away from the physics content, but that the teaching of physics should be viewed in the context of what students learn (Redish E. , 1994).

2.2.2 Context

Why can't we understand everything at once, instead of having one thought after another? In the constructivist concept, the information, or the simultaneous memories, in our minds, and the new information we obtain is organized and reshaped into mental models. The mind can be seen as a device that builds mental models to make sense and order out of our world (Johnson-Laird, 1983). In physics education, the constructions of mental models can be viewed as concepts, visions, and rules for certain actions and statements (Redish E. F., 1996). Our initial mental models can be incomplete and contradictory, and the elements in them may not be well defined. When we learn new concepts, we are working with our mental models. We organize and classify these concepts, which lead to the process of restructuring the models and then produce new knowledge.

One typical characteristic of a mental model is that it is context dependent. The context can be a situation, place, other people or a phenomenon to which the mental model is applied. Thus, the mental model can also be regarded as a way in which we construct our understanding of physics and its relations. In this study, mental models were taken to be the frame which the interactions and relations of electricity and magnetism are dealt with. The physical models are organized hierarchically into a construction of the physical theory. It is typical of a theoretical model that it is generic rather than contextual (Redish E. F., 1996).

The theoretical framework may include superior and inferior levels or sub-models concerning the same phenomena but with different areas of qualification and different usability. A higher-level theory may include lower-level theories as a simplified outcome due to narrowing boundary conditions. For example, take the case of deriving electric field magnitude at a given location in the proximity of a known group of point charges; Gauss's law for an electric field is seen as the highest theoretical framework. However, the Coulombian field concept is simpler to use in the case of discrete point charge distributions. Recalling the definition of von Wright (von Wright & Rauste-von Wright, 1994), we can say that the mental model, as it represents our knowledge, we use in physics is justified by rationalizing the meaningful use in different contexts. One aim of the instruction is to get the students to learn to choose and justify the use of a good approach, theory or procedure in a given situation based on their knowledge of the physics; the principles, laws and links between different contexts. Initially, however, the students approach problem solving by trying to solve equations directly based on information that is fragmented in different contexts (Brown, Collins, & Duguid, 1989)(Glaser R. , 2000).

Physical theories are results of a theoretical evolution. They have been developed to explain the previous and present observations. A good theory explains the phenomena that the theory should cover and offers predictions for new experiments. Also, a good theory should be repairable if something unexpected happens. According to Redish (Redish E. F., New Models of Physics Instruction Based on Physics Education Research., 1996), contextuality has two consequences. It is difficult to learn something that we do not already know, and everything we learn is learned via interpretation within a context. The learning of something becomes easier if it matches or extends existing mental models. Hence the physical theory, as a model, and the mental models of understanding have similarities. Thus, it is important to identify the features of the existing mental models of the students, as well as the model of the physics issue to be taught. This is also the theoretical background for using the model of Educational Reconstruction (see below), in which there are the elements of analyzing the students' prior knowledge and the content structure of the physics.

2.2.3 Change

It has been shown (Redish E. F., 1996) that reading and traditional lectures are ineffective methods for changing the mental models of the majority of students. Mental models can be changed via assimilation or accommodation (Piaget J. , 1977)(Redish E. F., 1996). Piaget's definition of accommodation and assimilation, in the case of children, is based on the idea that the organism adapts to its environment, and cognition is one form of adaptation (Piaget J. , 1977). In the assimilation process of learning physics, as interpreted by Redish (Redish E. , 1994), new ideas are linked to existing mental models without changing the model itself. When observations agree with an existing explanation, the mental model is easily adopted and assimilated. Additionally, in the accommodation process, observations that clearly belong to the domain of the mental model but are contradictory to the assumptions may lead to a changing of the model. This contradiction can be understood as a cognitive conflict in which the unexpected observation is not discarded but leads to the abandoning of the original model in favor of a more sophisticated one that is in accordance with the new observations (Chinn & Brewer, 1998)(Posner & Strike, 1982). Actually the mechanism of the cognitive change of the assimilation and accommodation process is relative and depends on the learner's original mental model. Indeed, each learner constructs his/her own knowledge based on his/her own experiences and learning history and this leads to variability, which should be taken into consideration.

2.2.4 Variability

"A class in which students are always passive is a class in which neither the active experimenter nor the reflective observer can learn effectively. Unfortunately, most engineering classes fall into this category."
-Richard M. Felder.

The students' individual ways of learning manifest themselves in their responses to the "stimulation" of teaching. One student learns better by listening to a teacher who has a good narrative facility, while another focuses on the visual representations. There are also students who likes to write and draw everything themselves, while other students use abstractions as formulas for supporting their understanding during the learning. Unfortunately, many teachers use only one or at best a narrow selection of learning styles (Felder, 1988).

According to Redish (Redish E. F., 1996) individuality has two consequences. Firstly, there is no unambiguous answer to the question of which method is the most suitable for teaching.

Secondly, teachers' own experiences of learning may not have exposed them to the best practices in teaching.

When interpreting the constructivist principle, active thinking is the key to quality learning. This activity arises from motivation, a challenging learning task and the goals of the learning process. In addition, an important aspect of quality learning is the metaconceptual awareness (Mikkilä-Erdmann, 2001) of the learner. This can be attached to the mental models used in teaching: *what* the model is, *why* the model should be learned and *how* to use the model.

2.3 IMPLICATIONS FOR PRACTICE

The next sections explore the implications of the theory of learning presented above.

2.3.1 Constructivism

The instructional interventions in this study, as described in articles III and V, included several small group tasks carried out during the lectures. These tasks offered a stage for the students to discuss the issues. In addition, there were several occasions when students commented on the steps they noticed in the learning process. They remarked that their knowledge originates from the knowledge of the instructor and then becomes the knowledge of the "classroom" and finally becomes the knowledge of the students. This represents a sociocultural view of learning where participation in the interplay of the social group is an essential mechanism of learning (Rogoff, 1990)(Leach & Scott, 2003). This procedure was followed in reverse order at the weekly problem solving situations. There, the students presented their solutions to the problems, after which the audience asked questions about the reasoning behind the solutions or asked for details in the solutions.

Although the instructor was present, the class actively and independently discussed the validity of the solutions. Indeed, problems can often be solved in different ways. Sometimes the problem was solved in a way that was new to the instructor. On these occasions, the knowledge comes from the student, becomes the knowledge of the "classroom" and then becomes the knowledge of the instructor. There were a few cases in which the student's solution changed the instructor's knowledge. We can summarize this by saying that the aim of the learning in constructivist ways consists of interaction between the learner and the social group, in which the process of understanding increases the learner's knowledge base.
The constructivist learning process is partly individual and partly social. The teacher's role in a constructivist learning process can thus be seen as setting the framework for learning and representing the culture of experts in physics. Furthermore, it is the teacher's duty to support the learner in his/her learning efforts, to assist in developing metaconceptual awareness and to design the physical and social learning environment. This is done by modeling the learning task, scaffolding by altering the learning task so the student can solve problems or perform tasks that would otherwise be out of reach, and by reflecting the students' performance(Vygotsky L. , 1978)(Rogoff, 1990). However, instructors should be cautious about helping students too much with a task. Too much assistance could result in a non-reflective and superficial understanding of the concept/problem. It is important to connect the students' problem solving work to the disciplinary content skills (Reiser, 2002).

During the lectures the students were encouraged to form groups of three or four to do the tasks at hand. In general, throughout the course the students were advised to get together to solve the weekly homework sets. Such informal group work that supports the students' active participation in the learning process is in accordance with the constructivist idea (Meyers & Jones, 1993). It continues to be difficult, however, to identify where the learning of something takes place. It may occur during the formal instruction, during the time spent with peers in the informal situations or at some other time.

2.3.2 Context

According to the constructivist concept, the understanding of something can be described thus: *when we understand something, for instance a concept of something, we can rationalise the way we are using the concept and we can use the concept meaningfully in a new context* (von Wright & Rauste-von Wright, 1994). As an example of such understanding in this study, we can take the case of the Right -hand rules as described in Articles 4 and 5. Students tend to use a memorized conclusion for the specific cases to describe the magnetic forces and fields. A correct understanding requires that the Right -hand rules be taken into account as a solid foundation on which a cross production interpretation of the magnetic force and field relations can be constructed. Indeed, the context in which we are using our knowledge seems to be an essential aspect of learning.

As we investigate the students' mental models we recognize that they are often not in accordance with the desired physical model to be taught. There can be structural differences, blank areas or quite often objects that are not in the right ontological category (Chi, Slotta, & deLeeuw, 1994). One example of this is when students mix up the concepts of electric force and electric field. Also, the problems in adopting the field-related Maxwell's equations were shown to originate from a difficulty in shifting from the Newtonian model of the field to the Maxwellian model, as reported in Articles 1 and 2. Although the educational reconstruction process began with the analysis of the different models, the design of the new teaching focused on the change that is needed to achieve understanding of the concepts. However, it is very difficult to change an established mental model. Pouring information or knowledge into students' heads is impossible. The instructor has to locate the problematic parts of the learning path, and the students have to work with their mental models and understand why they need to change them.

2.3.3 Change

Learning about electromagnetism at the university level begins with introducing and recalling the basic principles, continues with the laws of interaction, and finally the theoretical foundation of Maxwell's theory. The students already possess a great deal of knowledge about electricity and magnetism. However, a large portion of this knowledge is fragmented and lacks a strong link to a scientifically acceptable construction or mental model. Due to this fragmentation, it is difficult to gain useful or well organized information on the students' initial ideas about electricity and magnetism. Thus it is important to know what changes should be made before taking action.

It was assumed that the domain of electricity and magnetism was already familiar to the students to a certain extent. In addition to the written pretests, students were interviewed in order to reach a deeper understanding of the reasoning models underlying their answers. The basic course at the university, however, introduces a group of new features, especially the concept of fields, the vector character of fields, and the mathematical representations of the field relations that include integral calculus. Fields and vectors are not emphasised at the secondary level. In addition, the basic rules of thumb, in many cases, seem to be given to the students without physical reasoning. Indeed, the mathematical treatment of the electromagnetic theory and especially the surface and path integrals with physical interpretation are new and challenging for the students. In short, we were dealing with the following changes in this research: a conceptual change promoting field-related thinking to which the details are attached, a change in dealing with the vector field, and a change in treating equations in three-dimensional vector formed integrals.

2.3.4 Variability

Based on the theoretical background, it can be stated that it is essential in physics education research to focus on the students' ability to use and develop their own thinking. Students' access to the subject varies. Some students prefer to listen, while others prefer to do their own thinking. Some prefer to manipulate algebraic expressions, while others want the same issues to be drawn as a graph or as a picture. Some students want to be guided step by step, while others try to do everything by themselves. Preferring one strategy over others does not necessarily imply they cannot use others. The students have developed their abilities based on their success in previous experiences. Physics instruction includes various means of representing the ideas and issues: mathematically, graphically, narrative, or by describing processes. The students who initially prefer one approach learn and develop others later (Redish E. F., 1996).

Even though the aim of instruction is to change and develop the students' conceptions, it is essential to understand the initial conditions and assumptions concerning their knowledge, conceptions and misconceptions. When developing the content to be taught, it is not enough to just develop the whole process. In order to teach the conceptions, we have to find and develop methods through which the students can understand the concepts and develop mental models which they would not arrive at spontaneously. Frequently, lectures began with discussions that encouraged the students and the instructor to explain how they know or understand something. The students were also regularly invited to present not only the solutions to the weekly problems and final exams, but also a short description of the reasoning that led to their answers. This reasoning can be displayed as a mind map or a solution roadmap, as we called it. It included the leading principle, ground rules, physics laws (also conservation ones), and links between the contexts that best describe the given problem, and acceptable ways of constructing the solution. This guidance in developing metaconceptual awareness is, on one hand, very challenging for the students (they claimed in the course feedback that these situations gave them headaches), but on the other hand, as they also said in their feedback, it was one of the best ways for them to learn.

3 Educational Reconstruction

As a framework for the general strategy, the design and development of the teaching sequences were based on the model of Educational Reconstruction. This is in the German Didactic tradition, where the content structure of the physics under inspection is transformed into content structure for instruction (Duit;Niedderer;& Schecker, Teaching physics, 2007). The model of Educational Reconstruction has been developed as a research framework in science education, but it is also suitable for designing instruction (Duit R. , 2000). Indeed, the model has been used in a variety of science teaching and learning sequences: for example, in chaos theory(Duit, Komorek, & Wilbers, Studies on Educational Reconstruction of Chaos Theory, 1997), teaching non-linear systems(Komorek & Duit, 2004), teaching biology and microbiology(Hilge, 2001), explaining tides(Viiri, 2000), and teaching the moment of force(Nurkka, 2006). In this study, educational reconstruction was used in two cases. The first dealt with the design and evaluation of the teaching sequence of the electric field and force concept (Article 3) and the other dealt with the magnetic field and force (Article 5).

3.1 THE MODEL OF EDUCATIONAL RECONSTRUCTION

The model of Educational Reconstruction is based on three main components, which together constitute a cyclic process. Educational Reconstruction emphasises the close connection between the theoretical and practical aspects of designing teaching sequences in physics. It brings the science content and the educational issues together when teaching and learning sequences are being designed (Figure 2).

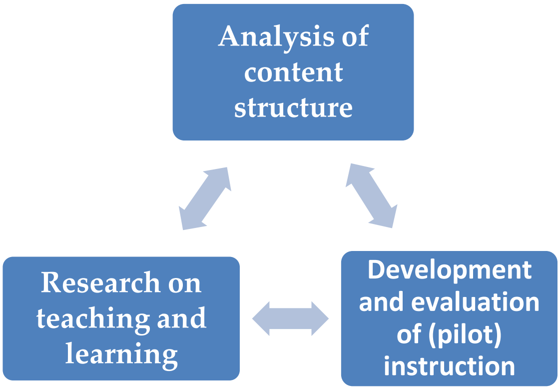


Figure 2. *The model of Educational Reconstruction. Adapted from the model presented by Duit (Duit R. , 2007).*

The analysis of the content structure deals with clarifying the physical theory of the electro- and magnetostatics from an educational point of view. This process of analysis is called *elementarization* (Komorek & Kattmann, 2008). The aim of this is to identify the central principles and theoretical nodal points that are relevant to the relevant domain. The process of elementarization provides the essential basis of the whole cycle of educational reconstruction. Influenced by the findings of research on teaching and learning and the development and evaluation of instruction, elementarization reshapes the material to construct content structure that can be used in the actual teaching. The outcome of the Educational Reconstruction process is a set of practical guidelines for teaching that take into account the aims of the teaching, the teacher's views, and the students' preconceptions and learning problems.

3.2 THE PHYSICS CONTENT AND ELEMENTARIZATION

The analysis of the content structure involves carefully considering the topics to be taught in a way that the aims of the instruction and the students' conceptions are taken into account. In physics, theory formation is often a result of scientific evolution resulting in compact and abstract forms and formulas for displaying the physical principles, relations, and laws. There is no point in reinventing this information for instructional purposes. Rather, the content structure for instruction has to be richer than the science content structure since it has to be embedded into the contexts that are accessible to and understandable by the learners(Duit R. , 2000)(Duit & von Rhöneck, 1997)(Duit R. , 2007). This can also be done by respecting the scientific models and the aims of the instruction. In this study, the issues under investigation were the concepts of electric and magnetic fields and forces.

The starting point for the subjects studied at the university level is generally the material learned at the secondary level. Regarding electromagnetics, the main difference between these two levels is that at the university level the theory covers the field-related Maxwell's equations. This difference has several consequences that explain the difficulties that students have. Firstly, the concept of a vector-formed field is an essential explanatory element in the relations. Furthermore, the concept of vectors describing the field is new and difficult for the students. Secondly, there are other new ideas, supporting concepts, such as surfaces and oriented paths, which are described with vectors. Surface vectors are combined with the field concept to form yet another abstract concept: electric and magnetic fluxes. Thirdly, the mathematical treatment of Maxwell's equations requires manipulation of vector-formed fields, surface and path integrals, and vector cross products. To some extent these are new methods for the majority of first-year students at the university. The fourth consequence is the physical interpretations of the field-related relations and equations; what they are actually describing, under which limiting conditions and how they are used in problem solving.

In a nutshell, the secondary school introduces more or less the same topics of electromagnetics as the university level basic course. However, the secondary level adheres to simple, one-dimensional, scalar-formed descriptions with a limited area of qualifications, which of course satisfies the standards of the secondary level. Some students at university, however, choose branches of science or engineering which include studies on electromagnetics. For these students, the instructors have to build bridges over the gaps in their knowledge. To do this, one starting point is to find out what was taught at secondary level, and compare it with what will be taught at the university level. However, studying the students' preconceptions reveals even more precise information that is useful in the process of designing effective instruction. One theoretical approach for structuring elementarization is by answering the key questions of the educational analysis (Klafki, 1995):

a) *What is the general idea that is represented by the contents of the immediate topic of interest? Which basic phenomena or basic principles and which general laws can be addressed in an exemplary way as a result of dealing with the content?*

b) *What is the significance of the immediate content or the experiences, knowledge, abilities, and skills that will be developed by dealing with the course content in the students' actual intellectual lives? What significance should the content have, from a pedagogical point of view?*

c) *What is the significance of the content for the students' future lives?*

d) *What is the structure of the content when viewed from the pedagogical perspectives outlined in questions a) and b)?*

e) *What are the particular cases, phenomena, and situations that help to make the structure of the specific content interesting, worth questioning, accessible, and understandable for students?*

The same questions that are used to construct the content of the instruction can be used when reflecting upon the results of the whole process. The outcomes of the answers to the key questions are presented in the next section where the nodal points of the instruction and the learning problems are considered together with the new instructional approach. The answers to the key questions on electrostatics are presented in more detail in Article 3.

3.3 RESEARCH ON THE TEACHING AND LEARNING OF ELECTROMAGNETICS

It is difficult to suddenly change existing constructions of knowledge. However, such a change is an important aim of learning and teaching the sciences (Komorek & Kattmann, 2008). Before we can learn a new concept, we need to re-conceptualize possible misconceptions that interfere with the learning (Bransford, Brown, & Cocking, 2000).

In this study, the students' preconceptions concerning electric and magnetic fields and forces were studied. In addition, the findings of previous studies were also reviewed. Articles 1, 2 and 4 are concerned with the backgrounds of the students' pre-instructional ideas upon which the designed instruction was built. Educational Reconstruction is open to different methods of inquiry regarding the students' conceptions. In this study, several approaches were used for this purpose. Also, preliminary ideas about troublesome issues were formed after the teaching experience, taking into account the results of final exams and the weekly feedback during the problem-solving lessons. The emphasis was on the field, force and vector-formed relations, and on the graphical representations and certain rules of thumb for fields and forces. This was in accordance with the findings concerning the new objectives to be taught at the university level, which are presented in the elementarization section. To obtain a general baseline performance on electromagnetics, certain tasks from the CSEM and BEMA tests were used as pre-tests and post-tests(Maloney, O'Kuma, Hieggelge, & Van Heuvelen, 2001)(Ding;Chabay;Sherwood;& Beichner, 2006). In order to acquire more detailed information on the students' thinking and preconceptions, semi-structured interviews on electromagnetism were carried out. (Drever, 1995)(Wengraf, 2001). Throughout, Educational Reconstruction worked in all directions. The elementarization guided the more empirical part inquiring into students' knowledge, and the results of the students' interviews were the starting point for more careful analysis of certain parts of the elementarized theory. Furthermore, iterations through the instruction sequences and new experiences affected the teacher, the new ideas, and the findings for improving the process emerges. Hence, the results of this whole study seem to be able to display within the process of educational reconstruction.

The iterative process of Educational Reconstruction led to the structure of the gradually propagating sequence of instruction, or steps, as I call them in the articles. The steps go through the nodal points of the material to be taught by taking into consideration the findings of research on learning and teaching in the domain.

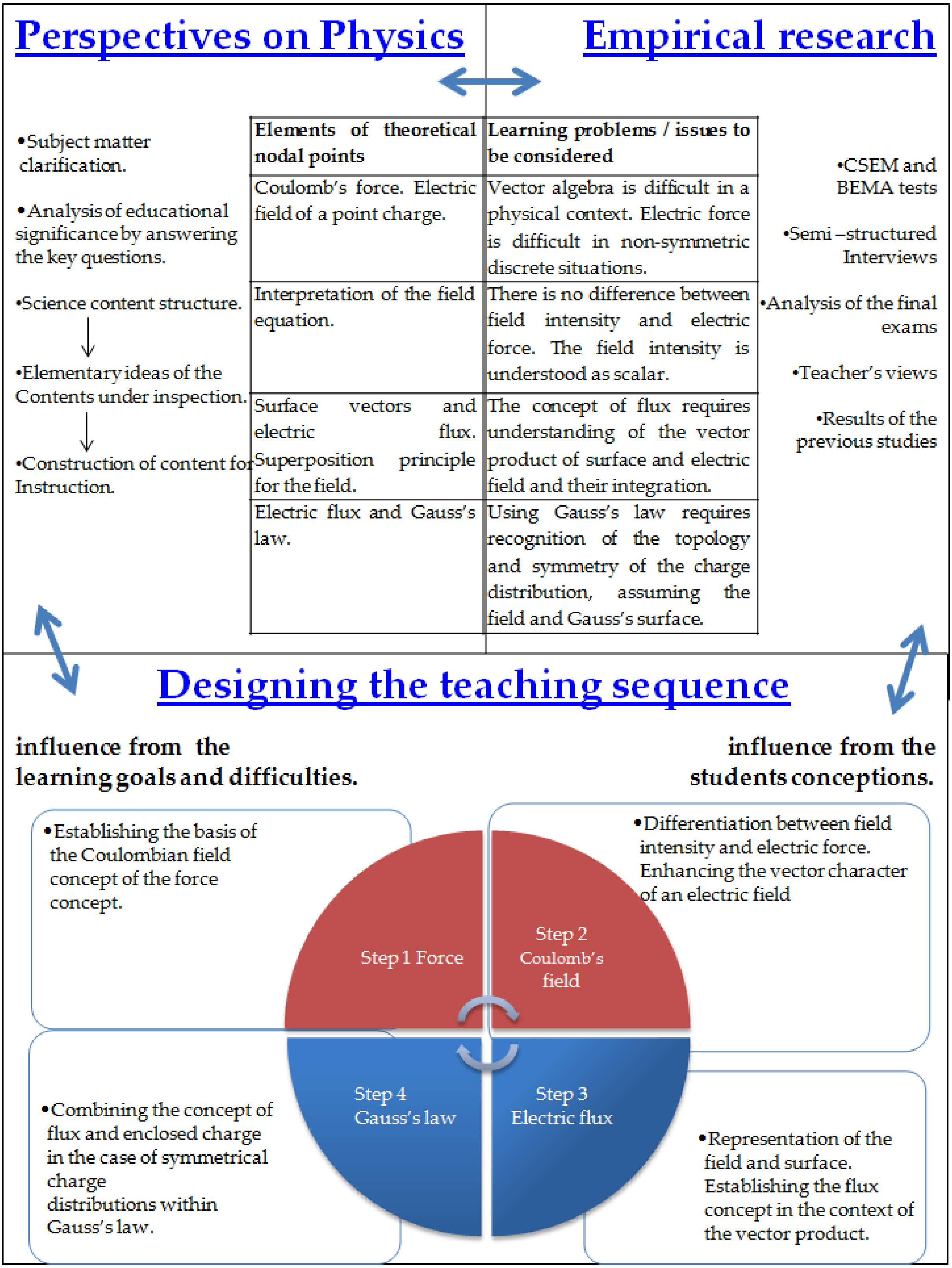
3.4 DEVELOPMENT AND EVALUATION OF THE PILOT INSTRUCTION

A teaching sequence designed according to the model of Educational Reconstruction must be based on the students' specific needs and on their potentials, learning difficulties, and interests in order to reach the aims of the instruction (Komorek & Kattmann, 2008). Designing the instruction requires putting together the ideas obtained from the elementarization and the students' pre-instructional conceptions (Brown & Clement, 1989)(Redish E. , Implications of cognitive studies for teaching physics, 1994). The challenge in reorganizing the learning tasks and assessments is to avoid increasing the students' work load.

A better understanding would be achieved by working with the exploitable features of the students' conceptions and reorganizing and reconnecting them so that they accord with the science concept. A good example of this would be the case of the

Right -hand rule as presented in Article 5. In short, the students adopted the scientific concepts of the magnetic force law and Biot-Savart's law when they were able to connect the vector cross product in the relations to their model of the Right-hand rule. They found the rules to be applicable and helpful only when they had understood of cross production and its physical interpretation.

Figures 3 and 4 shows the modified models of the educational reconstruction as a whole. They form a rough scale strategy framework of the research. The schemes related to electric and magnetic fields and force both follow the same pattern procedurally. The diagrams in figures 3 and 4 consist of the triangular interrelated issues of perspectives on physics, empirical research and designing the teaching sequence, according to the model presented by Duit (see Fig. 2 at the beginning of this section). The diagrams also show details of the learning difficulties, aims of instruction, and a rough scheme of the teaching sequence. The next chapter also brings together the strategic approach of the study (Educational Reconstruction) and the background and practical outcome of the instruction, which will be explored in the next chapter.



Perspectives on Physics

Empirical research

- Subject matter clarification.
- Analysis of educational significance by answering the key questions.
- Science content structure.
  ↓
- Elementary ideas of the Contents under inspection.
  ↓
- Construction of content for Instruction.

Elements of theoretical nodal points	Learning problems / issues to be considered
Coulomb's force. Electric field of a point charge.	Vector algebra is difficult in a physical context. Electric force is difficult in non-symmetric discrete situations.
Interpretation of the field equation.	There is no difference between field intensity and electric force. The field intensity is understood as scalar.
Surface vectors and electric flux. Superposition principle for the field.	The concept of flux requires understanding of the vector product of surface and electric field and their integration.
Electric flux and Gauss's law.	Using Gauss's law requires recognition of the topology and symmetry of the charge distribution, assuming the field and Gauss's surface.

- CSEM and BEMA tests
- Semi –structured Interviews
- Analysis of the final exams
- Teacher's views
- Results of the previous studies

Designing the teaching sequence

influence from the learning goals and difficulties.

influence from the students conceptions.

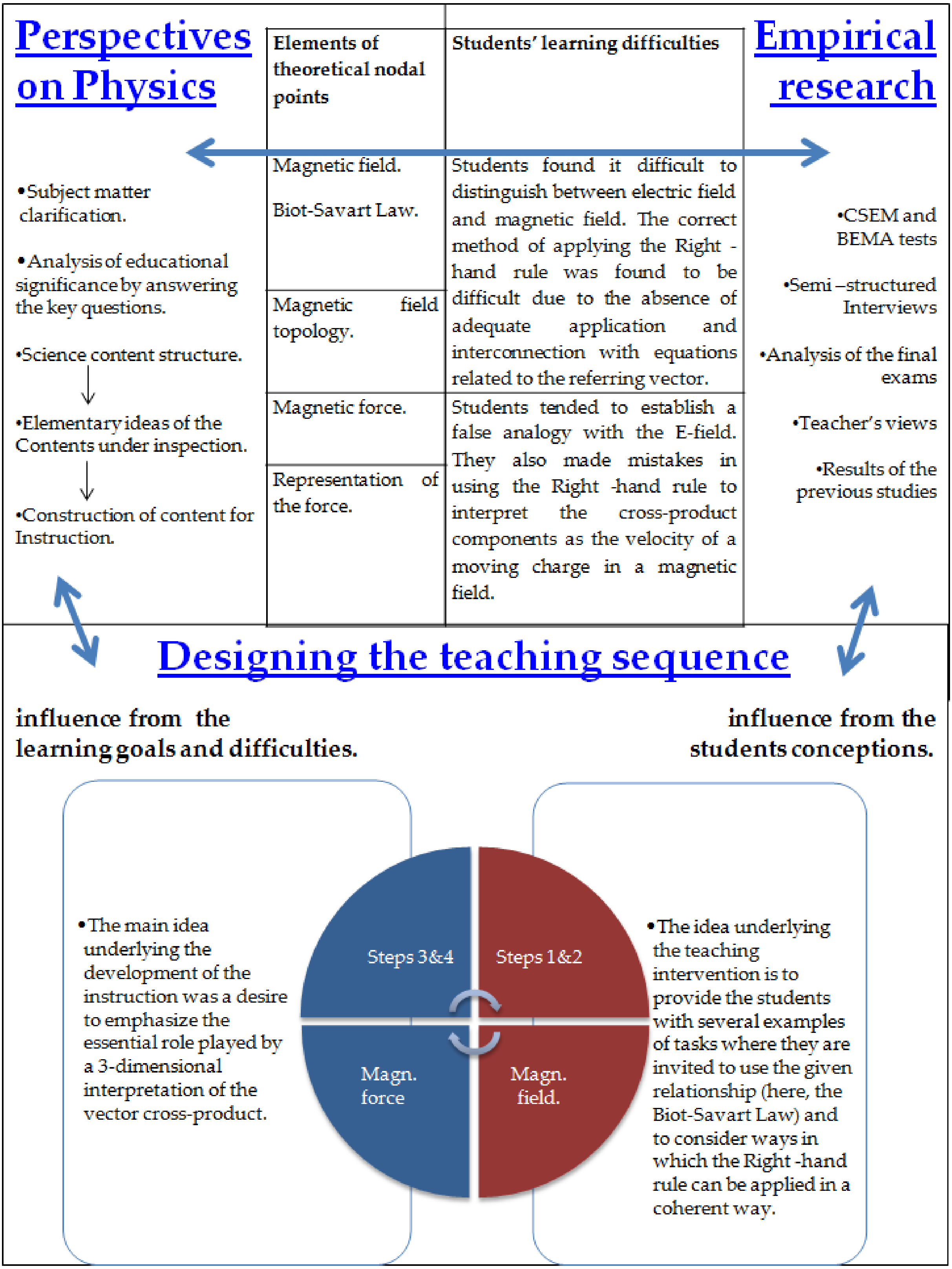
- Establishing the basis of the Coulombian field concept of the force concept.

- Differentiation between field intensity and electric force. Enhancing the vector character of an electric field

- Representation of the field and surface. Establishing the flux concept in the context of the vector product.

- Combining the concept of flux and enclosed charge in the case of symmetrical charge distributions within Gauss's law.

Figure 3. Diagrammatic presentation of Educational Reconstruction of electrostatics.



Perspectives on Physics

- Subject matter clarification.
- Analysis of educational significance by answering the key questions.
- Science content structure.
- Elementary ideas of the Contents under inspection.
- Construction of content for Instruction.

Elements of theoretical nodal points	Students' learning difficulties
Magnetic field. Biot-Savart Law.	Students found it difficult to distinguish between electric field and magnetic field. The correct method of applying the Right - hand rule was found to be difficult due to the absence of adequate application and interconnection with equations related to the referring vector.
Magnetic field topology.	
Magnetic force.	Students tended to establish a false analogy with the E-field. They also made mistakes in using the Right -hand rule to interpret the cross-product components as the velocity of a moving charge in a magnetic field.
Representation of the force.	

Empirical research

- CSEM and BEMA tests
- Semi –structured Interviews
- Analysis of the final exams
- Teacher's views
- Results of the previous studies

Designing the teaching sequence

influence from the learning goals and difficulties.

influence from the students conceptions.

- The main idea underlying the development of the instruction was a desire to emphasize the essential role played by a 3-dimensional interpretation of the vector cross-product.

- The idea underlying the teaching intervention is to provide the students with several examples of tasks where they are invited to use the given relationship (here, the Biot-Savart Law) and to consider ways in which the Right -hand rule can be applied in a coherent way.

Figure 4. Diagrammatic presentation of Educational Reconstruction of magnetostatics.

4 The Teaching-Learning Sequence

4.1 SETTING THE STAGE

At the University of Eastern Finland, the location of this study, two lower level physics courses are offered. The first one is for first-year students and it deals with the basics, whereas the other course covers more advanced field theory with extensive mathematical tools. The textbooks for these courses are University Physics with Modern Physics (Young & Freedman, 2008) and The Fundamentals of Electromagnetic Field Theory (Guru & Hizirogly, 2004). The research in learning and teaching was carried out in the first course. The basic course covers classical electromagnetics - Maxwell's equations together with the Lorentz force in their integral form in a vacuum. Maxwell's Equations by James Clerk Maxwell 1865, holds the top position in the equations of all times (Crease, 2004). However, they are the result of the work of several physicists during the 19th century and were put together by Oliver Heaviside in 1884 in the form that we now have them (Lindell, 2009).

Preparation for the first course at the University of Eastern Finland began 2004-2009 by examining the base line performance in electricity and magnetism by using the CSEM and BEMA tests. These tests covers the same main topics that are introduced also during the course; electric charge, electric force, electric field, voltage, electric current, capacity, energy, circuits and electric classification of material. All of the previous can be put into context that the electric field and its behavior can be found as a powerful explanatory concept. In the same way, electromagnetic induction or explanations of the different magnets are best described using the magnetic field concept.

Thus, correctly understanding the basic features of both fields is essential if students are to successfully complete the electromagnetics course.

4.1.1 Instructional approaches

Some instructional approaches to overcoming the difficulties involved in learning electro- and magnetostatics had been reported previously. One approach is to follow the traditional sequence of the development of electromagnetic theory (Binnie, 2001)(Serogloy, Koumaras, & Tselfes, 1998). The history of science is not linear, in the way presented in the textbooks (Pocovi & Finley, 2003). Nevertheless, the experimental work that can be performed in a classroom enhances the excitement of discovery and thus makes the content more accessible for some students (Cavicchi, 2003).

In one instructional approach at the secondary level, students, who were regarded as "junior researchers", carried out small-scale research on electrostatics. The aim was to provide them an opportunity to formulate the concepts of the basics of electricity (Furio & Guisasola, 2003). Guisasola also reports an instructional approach where the emphasis was on recognizing the sources of a magnetic field and on explaining the magnetic field in qualitative terms for different phenomena (Guisasola & Almudi, 2009). Viennot and Rainson reported an example of studying the charged conductors in equilibrium, where the concepts of electric field and the superposition principle are relevant, more precisely understanding the boundary conditions principle in the surface of charged objects (Viennot & Rainson, 1999).

Traditionally, at the undergraduate level, Gauss's Law is introduced in the early stages of the course, prior to the concepts of potential, capacitance, and current. However, Gauss's Law deals with troublesome derivations and it is too abstract for the students to adopt as a starting point in learning electrostatics.

Chambray (Chabay & Sherwood, 2006) suggests rearranging the structure of the introductory course on electromagnetics. By postponing Gauss's Law, the students get an easier start to developing their basic skills and the concepts in electricity before encountering Maxwell's equations (Chabay & Sherwood, 2006).

Marr (Marr, 1999) devised an instructional approach related to magnetostatics at university level in which a four-step modification of homework exercises was designed to improve students' basic skills in problem solving. The steps included units, a routine of mathematical problems, conceptual problems and physics problems (Marr, 1999). The fact that Maxwell's equations are coordinate independent makes it possible to study the magnetostatics also from a weak relativistic perspective (Galili & Kaplan, 1997).

These approaches are related to the known learning difficulties of recognizing the source and the general problems related to problem solving. A Furio's and Guisasola's approach deals with learning the field-related vector concepts of the fields and interconnecting them meaningfully to the corresponding relations. Chabay's way of restructuring the topics of the course would make the approach to Gauss's law easier because students would learn electricity-related issues first. Nevertheless, restructuring the broad topics does not affect the internal fine grain structure in teaching Gauss's law. The concepts of electric field and field relations still need to be dealt with in a new way in order to enhance the students' understanding of a field vector and make it more accessible to them.

In the following sections, I present the theoretical nodal points of electromagnetics that form the base for field concepts. These sections form the "corners" of the triangular displayed in figure 2 i.e. perspectives on physics and the empirical research in the strategy of educational reconstruction. The next section presents the instructional interventions, or steps. These are the "corners" of Educational Reconstruction concerning the designed teaching sequence.

4.2 PERSPECTIVES ON ELECTRIC FORCE AND FIELD

Table1, which also can be found in Figure 3, presents the known learning difficulties, aims of instruction, and ideas of the instructional approaches.

Table 1. *Elements, learning problems and steps in teaching and learning electrostatics.*

Elements of theoretical nodal points	**Learning problems / issues to be considered**	**Content structure steps**
Coulomb's force. Electric field of a point charge.	Vector algebra is difficult in a physical context (Melzer, 2003). Electric force is difficult in non-symmetric discrete situations. (Teacher's view)	Step 1: Establishing the basis of the Coulombian field concept of the force concept. (Teacher's view)
Interpretation of the field equation.	There is no difference between field intensity and electric force. Neglecting the vector character of the electric field (Furio & Guisasola, 1998). The field intensity is understood as scalar (Saarelainen, Hirvonen, & Laaksonen, 2007).	Step 2: Differentiation between field intensity and electric force. Enhancing the vector character of an electric field (Furio & Guisasola, 2003).
Surface vectors and electric flux. Superposition principle for the field.	The concept of flux requires understanding of the vector product of surface and electric field and their integration. (Teacher's view).	Step 3: Representation of the field and surface. Establishing the flux concept in the context of the vector product. (Teacher's view)
Electric flux and Gauss's law.	Using Gauss's law requires recognition of the topology and symmetry of the charge distribution, assuming the field and Gauss's surface. (Teacher's view)	Step 4: Combining the concept of flux and enclosed charge in the case of symmetrical charge distributions within Gauss's law. (Teacher's view)

The general aim of teaching the electrostatic theory is to introduce the first steps of electrostatics and their dependence in increasing hierarchical order: source (charge) ➔ electric force (Coulombian force) ➔ Coulombian electric field ➔electric flux ➔ Gauss's law (and Maxwellian electric field). This order of topics is similar to that found in the chapters of most university physics textbooks. The significance of the steps is the relation between force and field, how the field is derived from the force, and how the force and field are linked to each other. Furthermore, it is important to understand the relationship between the total electric flux through a closed surface and the enclosed charges (Gauss's law). The importance of understanding the electric field and Gauss's law for future courses is clear. The course on introductionary electromagnetics is followed by other courses such as electromagnetic field theory, optics, electronics, and courses in technology. The correct treatment of electrostatic phenomena and principles in earlier courses is essential if students are to cope with the higher level courses.

The aim of the instruction is to underline that the static electric field is a spatial vector field caused by a static charge distribution. During the instruction, the concept of electric field was emphasised by paying attention to the graphical and mathematical representation of the electric field vector and electric force acting on a test charge in the proximity of a distribution of simple point charges. Understanding of the vector concept was enhanced by giving several examples where Coulomb's field was derived for a distribution of point charges and for continuous charge distributions.

4.3 DESIGNING THE TEACHING SEQUENCE ON ELECTRIC FORCE AND FIELD

4.3.1 Step 1: Coulomb’s Force

Traditionally, the instruction of electrostatics begins by introducing Coulomb’s Law in the form found in Figure 5. Coulomb’s Law states that the force is dependent on the signs and magnitudes of charges as well as on the distance between the charges. The electric forces acting on a test charge are also studied in the cases of discreet and continuous charge distributions, which emphasises the concepts of superposition principle and forces as vectors.

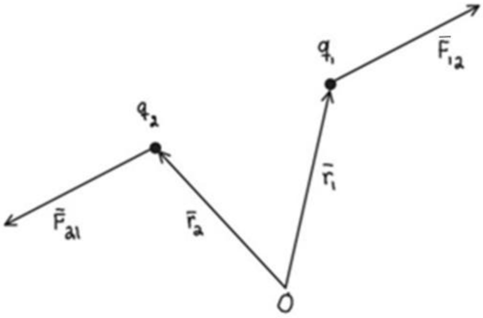


Figure 5. *Coulomb’s law for the electric force between point charges. The force acting on the charge q_1 is :*
$\overrightarrow{F_{12}} = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{|\vec{r}_1-\vec{r}_2|^3}(\vec{r}_1 - \vec{r}_2)$.

An example of the limitations of Coulomb’s Law is charging by induction. The static distribution of induced charges exists due to electric forces. However, the equilibrium precedes a dynamic relaxation process. Coulomb’s Law describes electrostatic forces that affect immediately, while the electric field responds to the movement of the charge with a delay.

4.3.2 Step 2: The Coulomb’s Field

The electric force vector gives the vector character to the Coulombian electric field. The field is formed by Coulomb’s force law by observing the relation between the electric force and the test charge as the test charge diminishes. By taking the

Coulombian field definition and applying the superposition principle and integration for continuous distribution, it is possible to derive the electric field in any point for a known charge distribution. The graphical representation of the field is closely connected to the mathematical description of the field as illustrated in Figure 6.

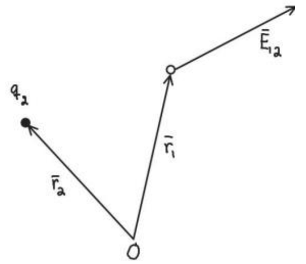


Figure 6. *Coulombian Field in the location r1 can be expressed as* $\vec{\boldsymbol{E}}_{12} = \boldsymbol{lim}_{q_1\to 0}\frac{\vec{F}_{12}}{q_1}$ *or* $\overrightarrow{\boldsymbol{E}_{12}} = \frac{1}{4\pi\epsilon_0}\frac{q_2}{|\vec{r}_1-\vec{r}_2|^3}(\vec{\boldsymbol{r}}_1 - \vec{\boldsymbol{r}}_2)$.

The instruction intervention included studies on the relation between electric force ($\vec{F}$) acting on a test charge (q) and the field $\vec{E}$ at that location caused by point charge distribution. The Coulombian field concept was formed from the relation $\vec{E} = \frac{\vec{F}}{q}$ by letting the test charge go down to zero. The point of observation was described by existing electric field intensity $\vec{E}$.

The instruction utilised two approaches. The first was to present examples that required the calculation of electric force acting on a test charge by several point charges in a non-symmetrical arrangement. The non-symmetry of multiple sources underlines the vector calculus in adding up the forces. Secondly, the electric field (Coulomb's field) was derived from the force by the relation $\vec{E} = \frac{\vec{F}}{q}$ and reshaped to the relation $\vec{F} = \vec{E}q$.

The theory of electrostatics is strongly based on the vector character of the electric field. Thus, the aim of teaching and learning the topic should be focused on this crucial aspect.

4.3.3 Step 3: The vector character of *E*

Instructional intervention to overcome the learning difficulties concerning the vector character of E dealt with the use of the Coulomb's field for a single point charge and distribution of point charges. In addition, the intervention dealt with deriving the field of continuous and symmetrical charge distributions (a ring, line, and a sheet of charge) using the concept of charge density (linear, surface, and volume) and integration. The innovation was to compare the graphical representations of the field lines and electric field vectors as shown in Figure 7.

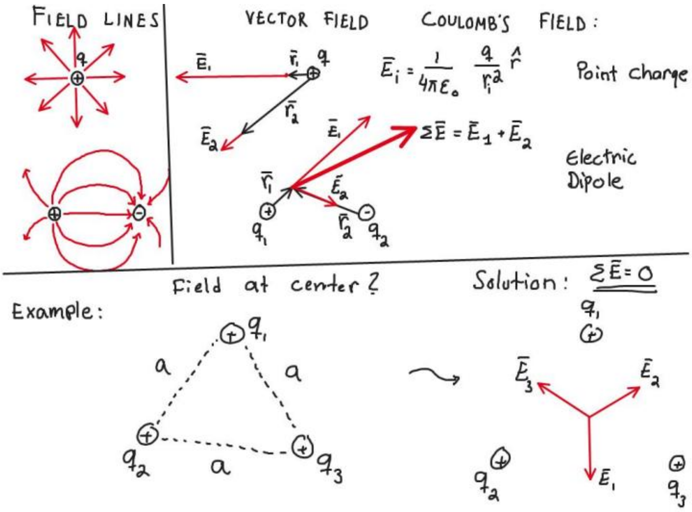


Figure 7. *Lecture example of comparing the different representations of the field.*

The field vector representation was strongly linked to the mathematical formulation, i.e. Coulomb's Field. The vector character of ***E*** arises from the definition of the position vector $\vec{r}$ and unit vector $\hat{r} = \frac{\vec{r}}{r}$.

4.3.4 Step 4: Using the field concept

The electric field vector is not only convenient but essential in dealing with electrodynamics and electromagnetic waves. In electrostatics, the field concept is also useful and justified. An example of the application of the field concept in electrostatics is the behavior of the conducting materials in external field. In

Figure 8, the external field, which goes inside the conductor, causes an induced charge distribution to the surfaces of the conductor. This distribution in turn causes an induced field inside the conductor, resulting in a zero net field when added to the external field at the equilibrium. The unbound free charges inside the conductor are at rest after the balance is reached.

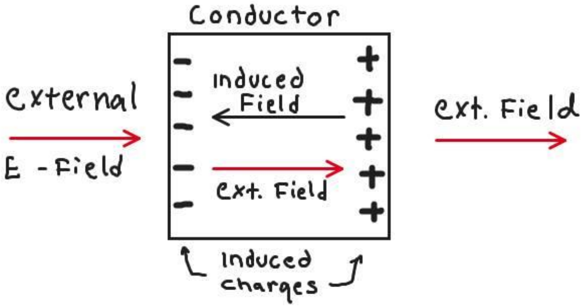


Figure 8. *Conductor in an external electric field*

The instruction continues by introducing Gauss's law. The mathematical treatment of Gauss's law includes flux integral containing dot products of the vector electric field and surfaces. Gauss's law connects the net flux on the surface to the algebraic sum of the charges inside the surface. This is different from the Coulombian field description in that the information of the charges – their magnitude and location – is now represented as the spatial function of the field. For symmetric and infinite distributions, Gauss's law gives the field on the surface or as a function of all the space instead of a value of a single location. The conceptual shift from the Coulombian model to the Maxwellian model can be found specifically here; the electric field derived by Gauss's law is no longer explicitly dependent on knowing the spatial function of the charge distribution, as is the case in the Coulombian field.

Figure 9 shows a lecture example of the method to describe the field, surface, and flux in Gauss's law.

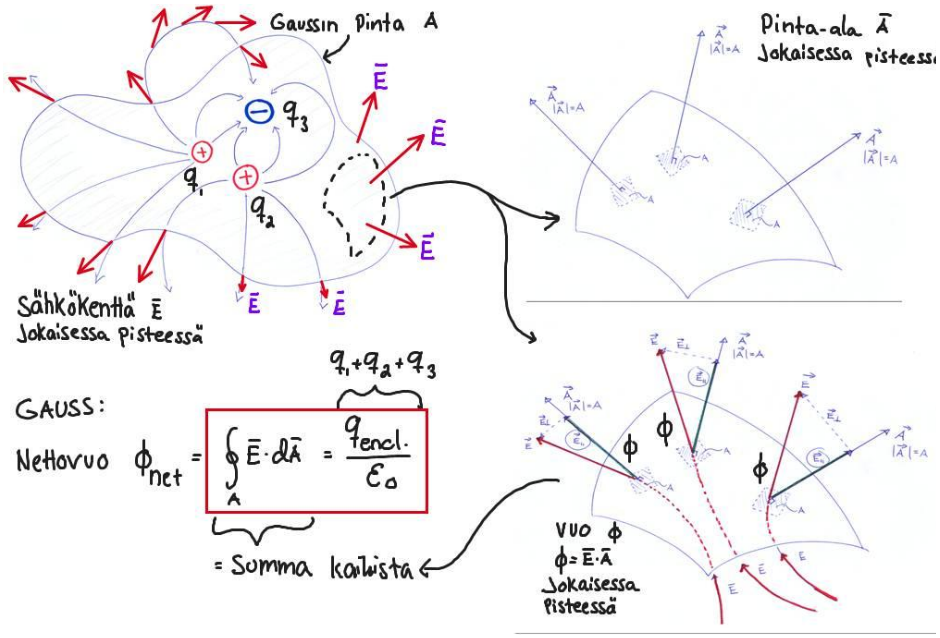


Figure 9. *Lecture example. "Point charges produce a net electric field in the vicinity. The field is spatial and has a certain vector value at each location. A non-material Gauss's surface is set enclosing the charges. The surface can be presented as vectors pointing outwards from the surface, each being perpendicular to the surface and having a magnitude equal to the area perpendicular to the vector. The flux of each location is a dot product of the static electric field vector and surface vector at that location. The net flux on the surface is thus a scalar value that is proportional to the algebraic sum of the charges inside the surface, according to Gauss's law. Note that the electric field vector and surface area vector are static and thus we say that the flux is "at the surface" rather than "through the surface".*

Note the drawing of the electric field vectors: they originate at the point where the field is represented. This is one outcome of paying attention to the fact that the electric field is a spatial vector function.

This Maxwellian model of the electric field differs from the Coulombian model in a significant way. The Maxwellian model presents the field as a description of space that is equal to the charge distribution in the vicinity via Gauss's law, while the Coulombian model – assuming that the field is a superposition of single point charges – attaches each individual point charge to the net field observed in the space. Supported by Faraday's law, the electric field close to the interface of two media leads to the electrostatic boundary conditions. The result is that the field near a charged surface can be treated as an entity that has mathematical symmetry, or equilibrium, with the charge distribution along the interface. This Maxwellian model of the field, as stated in step 4, acts as a starting point for further theory formation. One example of this is the case of a displacement current or electromagnetic waves. Some examples of the teaching material are presented in the following sections. In addition, materials used as lecture tasks are shown in the appendixes of Articles 3 (Saarelainen & Hirvonen, 2009) and 5. The entire course material that was produced by the instructor consists of 150 lecture examples (approximately 600 pages), 142 pages of theoretical lecture notes, and 197 figures.

4.4 PERSPECTIVES ON MAGNETIC FIELD AND FORCE

Whereas electricity is familiar to the students from several examples and applications, magnetism is familiar merely from experiences with permanent magnets. Playing with magnetic toys and "refrigerator magnets" creates the impression that the attractive forces are similar to those between a comb and a piece of paper; hence the explanation of magnetism often reminds one of the explanations of electricity. Furthermore, most students do not connect the origin of magnetism to the electromagnet or to the background of electromagnetism. The traditional textbooks often start dealing with magnetism by introducing the force acting on a moving charge (Young & Freedman, 2008). This, however, is quite puzzling since the approach requires the existence of the new field – the magnetic – to be interpreted. Unlike with electrostatics, we cannot begin with observations of forces between elementary magnets.

Traditional instruction involves the clarification of the cross products within the magnetic force law and the Biot-Savart law separately. The mathematical treatment and the physical interpretations are often turned into rules of thumb to simplify the needed three-dimensional visualization. Indeed, in the textbook adopted for this course, there is a short chapter introducing the concept of the magnetic field. This comes before the section dealing with magnetic forces, which I see as essential to avoid confusion about the electric and magnetic field. In addition, the role of the test charge is now taken by the compass needle with which the general directions of the field can be demonstrated. However, much of the section on magnetism is built on electricity analogues, and magnetic field is taught by defining *how* it differs from or resembles the electric field (Guisasola J. , 2004).

Magnetic behavior, the response of material to the external field, is far more complex than the similar case of electricity. Magnetic properties of material are due to their active participation in forming the field in space. While the electric field can only diminish inside the material depending on electrical susceptibility, magnetic material can give rise to magnetic field intensity inside the material. During the course, only the simple cases of different classes of para-, dia- and ferromagnetism are dealt with. Ferromagnetic material is dealt with by using a model of compass needles. The free electrons inside the ferromagnetic material have both an inherent electric charge and a magnetic property that is described as a tiny bar magnet. Now the bar magnet is also used as a model for a compass needle. Free to rotate and move, the bar magnets inside the ferromagnetic material follow the external field.

Based on Educational Reconstruction, Table 2 presents the aims of the instruction, the learning difficulties addressed, and the instructional approach.

Table 2*. Elements, learning problems and steps in teaching and learning magnetostatics.*

Elements of theoretical nodal points	**Content structure for instruction**	**Students' learning difficulties**
Magnetic field. Biot-Savart Law.	Steps 1 & 2: The idea underlying the teaching intervention is to provide the students with several examples of tasks where they are invited to use the given relationship (here, the Biot-Savart Law) and to consider ways in which the Right -hand rule can be applied in a coherent way.	Students found it difficult to distinguish between electric field and magnetic field. In addition, the correct method of applying the Right -hand rule was found to be difficult due to the absence of adequate application and interconnection with equations related to the referring vector.
Magnetic field topology.		
Magnetic force.	Steps 3 & 4: The main idea underlying the development of the instruction was a desire to emphasize the essential role played by a 3-dimensional interpretation of the vector cross-product.	Students tended to establish a false analogy with the E-field. They also made mistakes in using the Right -hand rule to interpret the cross-product components as the velocity of a moving charge in a magnetic field.
Representation of the force.		

The following sections explain how the magnetic force and field are dealt with in the instruction.

4.5 DESIGNING THE TEACHING SEQUENCE FOR MAGNETIC FORCE AND FIELD

4.5.1 Steps 1 & 2: Magnetic field and its representation

As was the case with the magnetic force, the magnetic field is also three dimensional, but rotational in nature. The illustration that most of the introduction to the magnetic field is attached is shown in Figure 10 below.

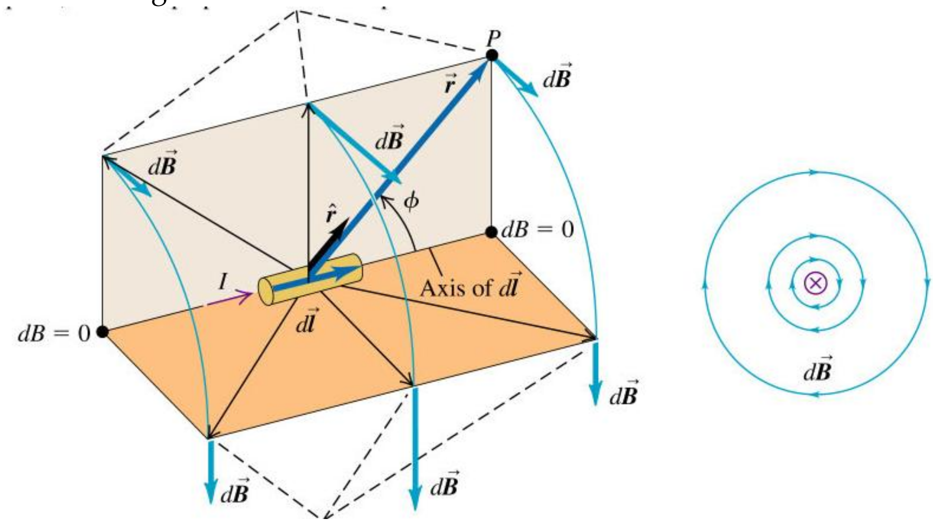
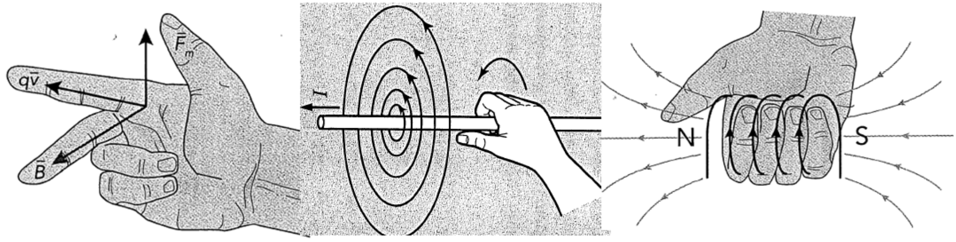


Figure 10. The Biot–Savart Law for a current element and a moving charge. The vector R is pointing from the element or a charge to the point of observation.A textbook illustration of the magnetic field created by a segment of DC wires (Young & Freedman, 2008).

The Biot–Savart Law is considered to be a starting point when a magnetic field $\boldsymbol{B}$ is derived from a moving charge q or a current element $I\boldsymbol{dl}$, are given $d\vec{B} = \frac{\mu}{4\pi}\frac{Id\vec{l}\times\vec{R}}{R^3}$ or $d\vec{B} = \frac{\mu}{4\pi}\frac{q\vec{v}\times\vec{R}}{R^3}$.

Biot-Savart's Law includes the idea of orthogonality between the direction of the current and the field. The Biot-Savart Law does this explicitly by giving the resulting magnetic field vector as proportional to the cross-product of an oriented wire segment and position vectors.

These interpretations of Biot-Savart's Law and magnetic force laws are often reduced to the so-called Right -hand rules that are applied in highly symmetrical and simple situations, as shown in Figure 11. Due to the complexity and high degree of abstractions involved in the precise explanation of the magnetic field and magnetic force, it is tempting to learn the outcome of simple cases – the Right -hand rule. If used logically and correctly, this certainly works in solving some problems.



a *b* *c*

***Figure 11**. Upper secondary school textbook illustrations of Right -hand rules for (a) magnetic force , (b) magnetic field of a DC wire, and (c) for solenoid(Eskola, Ketolainen, & Stenman, 2007)(Lehto, Havukainen, Leskinen, & Luoma, 2006).*

However, this is the domain of the use of the Right -hand rules at the upper secondary level (Hatakka, Saari, Sirviö, Viiri, & Yrjänäinen, 2007). The result of reducing the demand for vector calculus is that the referring relations are typically expressed in scalar form, and the directions should be memorized using the Right -hand rules. The Right -hand rules are context dependent and are not named after any specific situation.

The key to understanding the magnetic interactions lies in understanding how the 3-dimensional vector fields are formed from the sources and on which basis they cause force interactions. The aim of instruction at the university level is understanding the vector character of the field and force, and their cross production origins in the referring relations is essential for a deep understanding of the basic magnetic concepts. This can be regarded as a first step towards understanding the abstract model represented by Maxwell's equations.

4.5.2 Steps 3 & 4: Magnetic force and its representation

The magnetic interactions, i.e. the magnetic force, cannot be considered without the movement of the charge in the presence of the nonparallel magnetic field. Therefore, the formation of the field concept is not derivable from the force concept, as is the case with the electric field. The nature of the magnetic force, as well as the Biot-Savart Law, is three dimensional due to the cross product of the physical vectors. This is why instruction on these topics requires the use of selected illustrations and active search and trial with computer programs that help in visualizing the phenomena (Chabay R. , 2002). In addition, a variety of classroom equipment can be used. Students can even use their own bodies to act out the three-dimensional vector field and moving charges.

Magnetic force is a result of a cross-product of the current element and the magnetic field, causing the force and field to be perpendicular, as illustrated in Figure 12.

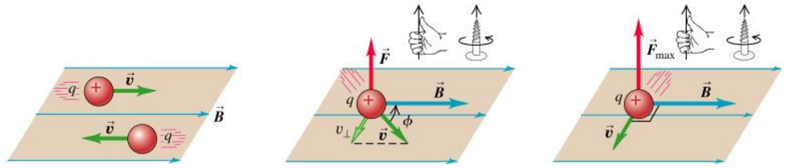


Figure 12. *Magnetic force law, which relates the vectors of the force (F), velocity (v) or the current element (dl) and the magnetic field (B).Illustrations of the magnetic force and the interpretation of the cross product (Young & Freedman, 2008).*

The magnetic force law can be expressed as $\vec{F} = q\vec{v} \times \vec{B}$ or $d\vec{F} = Id\vec{l} \times \vec{B}$.

The most important aim of the instruction on magnetic force is the physical interpretation of the cross product. Based on that, the referring problems can be solved by generalizing the elementary idea of the magnetic force concept and using it as a tool that can be applied to various situations. Often the rules of thumb that have been memorised are linked to some specific situation.

4.6 SUMMARY

The aim of the instruction is to enhance the electric field vector concept and thus make the field-related, i.e. the Maxwellian, theory more understandable. The electric field vector is associated with the charge distribution, and the magnetic field with the current distribution. Traditionally, the electric field concept is introduced first and thus the basic conceptual change towards adopting field conceptions in general relies on forming the electric field concept (Young & Freedman, 2008). The theoretical aspects of contextuality to be discussed later can be linked here. Instruction on the electric field concept begins with learning Coulomb's Law. Coulomb's Law is adequate for every case where a distribution exerts a force on a test charge, and thus it gives the referring electric field direction and magnitude at that point. Even though the Coulombian Field concept is accurate, it is difficult to use in many circumstances. Calculating the field by using Coulomb's Law requires knowing the exact charge distribution, which is not always an easy task. In addition, Coulomb's Force, from which the field is derived, is valid for static situations. It seems rather inefficient to introduce the Maxwellian model, i.e. Gauss's law, for electrostatics as it solves the same problems that Coulomb's Law does. Only some exceptions, such as continuous and symmetrical charge distributions, give Gauss's Law an advantage in comparison to Coulomb's Law. For example, the field outside a spherical charge distribution is easily solved using Gauss's law but it would require laborious triple integration with Coulomb's law. Adopting the field as an entity that describes the space in the proximity of a charge distribution as in Gauss's Law requires rejecting the need for any test charge to be present. Gauss's Law for the electric field is a clever way to solve problems related to the field and charge distribution.

Understanding the magnetic field and force as postulated in the Biot-Savart Law and magnetic force law is very important for the students' future learning. Successful learning of these topics depends on the correct treatment of the magnetostatics phenomena and principles. Emphasizing the magnetic vector field aspect in the instruction is essential, since the concepts in magnetostatics are generally field-related.

Maxwell's equations for electromagnetics are balanced and useful only with all components present, i.e. Gauss's Laws for electric and magnetic fields, Ampere's and Maxwell's Laws and Faraday's Law for induction. These four statements form the basis for electromagnetic theory. The common denominator in the equations is the concept of the field, electric or magnetic, as an entity. The fields are also associated with each other in electromagnetic induction, displacement current, and electromagnetic waves. Here, we see that the electric and magnetic fields are no longer the result of only static or moving charges.

5 Results

5.1 THE ARTICLES AS A WHOLE

The aim of this study was to develop effective instruction for electro- and magnetostatics. This was done using the Educational Reconstruction method for the whole project. It was decided that the scientific findings would be published as refereed journal articles and proceedings papers. The publication plan and execution was based on five papers that form a coherent group, as illustrated in Figure 13.

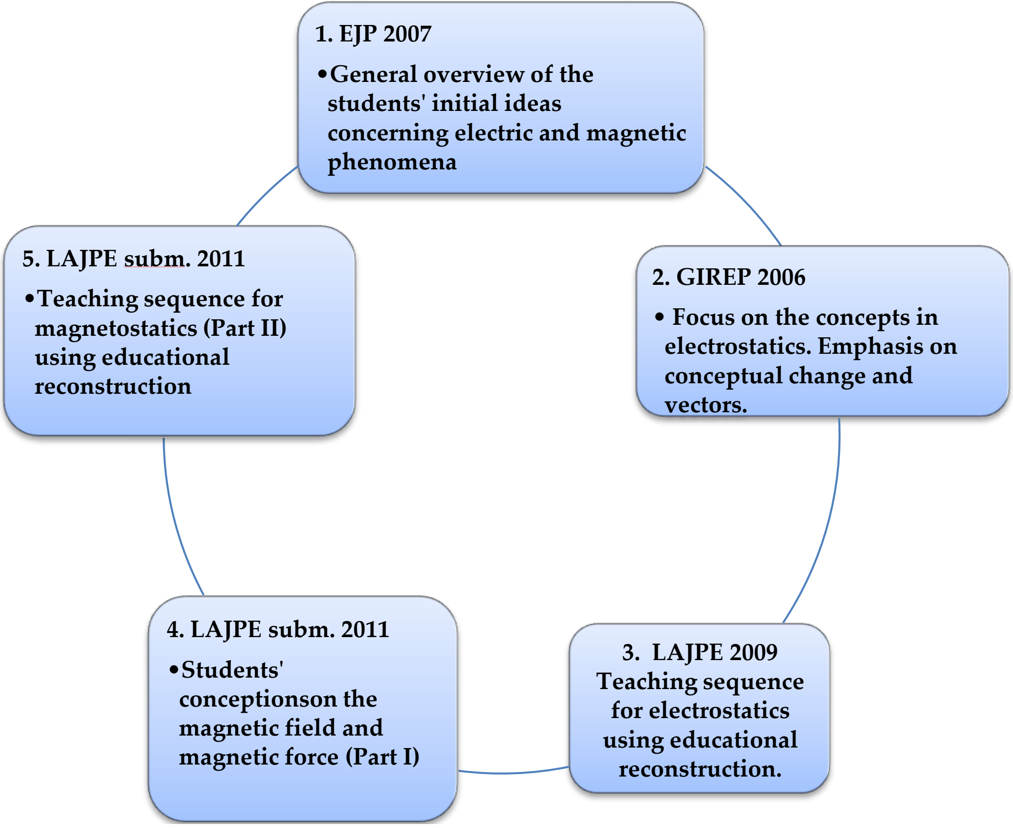


Figure 13. The cycle of the five articles covers the students' preconceptions on electric and magnetic fields and forces and the developed instruction.

In short, the first research report covers the general view of the students' initial conceptions concerning electric and magnetic phenomena (Article 1). Then the inquiry focused in more detail on electrostatics (Article 2). Based on the findings concerning the difficulties that most students have, the teaching sequence was developed to overcome these difficulties using Educational Reconstruction (Article 3). The last two reports go through an analogue process of searching for the most important pre-instructional concepts and learning difficulties (Article 4) that should taken into consideration for the development of new teaching sequences in magnetostatics (Article 5). Future research may follow an analogue cycle concerning the topics discussed in the conclusion.

5.2 MAIN FINDINGS

When planning the whole project there was naturally no specific information available on the findings that the research revealed. The following sections present the results reported in each article.

5.2.1 Article 1 results

The first article (Article 1) is actually chronologically the second one due to the simultaneous work on the publications and the GIREP 2006 conference. Information about the students' conceptions was acquired using two methods. The first method was to use written tests. The written tests (Conceptual Survey on Electricity and Magnetism, CSEM) gave the general baseline performance on the topics of electricity and magnetism. CSEM is a test that can be used in pre-instruction and post-instruction modes for the algebra/trigonometry-based and calculus-based introductory, college-level physics course. The other method involved semi-structured interviews that initiated discussions about the reasoning models underlying the students' answers. The results of the analysed interviews showed that the absence of appropriate vector thinking in case of the fields, and of vector field dependent concepts such as the flux, are the primary reasons for the vague use of the field concept in answering the CSEM questions 6, 23 and 29 That can be found in detail in Article 1. Vectors, in general, are used successfully by first year students in mathematics, but not in electromagnetics. The results suggest that students have qualitative ideas about repulsive and attractive electric forces. Some students used Coulomb's law and the electric force vector. However, the electric field line representation for ***E*** was left without a vector character and thus further interpretations for possible electric field vectors were not given. The students were not able to discuss electric fields properly, especially in situations where the charge does not interact with another charge.

Furthermore, the vector algebra needed in learning electromagnetics includes such new concepts as flux and path integrals, which confuse most of the students. Therefore it our findings are in line with the conclusions in previous research (Guisasola J. , 2004)(Dunn & Barnabel, 2000). The analysis revealed that the students were not capable of applying vector representations for electric fields even though they successfully treated electric forces as vectors. In addition, the students had only vague ideas on how to apply the "Right -hand rule" to more general situations. Students answered these questions fairly well on the test. In the interview the students understood well that a test charge at a specific location experiences Coulombian force due to another point charge. However, the follow-up question “what is the electric field at the same location without the test charge?” was answered poorly. Thus the main implication for the teaching sequence was to focus on vector thinking and on the concept of field.

5.2.2 Article 2 results

The students were familiar with the field line representation, but they did not know how it should be interpreted. They were unable to say what features of the electric field it manifests and what are the possible limitations of such a representation. For a single point charge, most students drew field lines originating from the charge, i.e. the radii. Some students did correctly interpret that the line density is proportional to the field strength. Two students said that the field is stronger closer to the charge and weaker further away from it, but they could not fit this information into the field line representation, thus could not draw an electric field vector in an arbitrary point. One of the students claimed that the field magnitude remains the same along the field line. This behavior of the field magnitude was similar to the case of two charges (A and C). It was difficult for the students to use only the field line representation to estimate the direction and the magnitude of the electric field at the observation point (B).

Indeed, the field line representation does not seem to link to the mathematical representation, i.e. the Coulombian field model for punctual charge. The field line representation should include information about the referring vector, i.e. direction and strength, in addition to the dimension of the vector. This is taken into consideration in the model of the vector field representation as introduced by Chabay & Sherwood (Chabay R. , 2002).

We found two main reasons for the undesired concepts. Firstly, the students showed an immature understanding of electric field as vector field. Vectors, in general, were not used as successfully in physical contexts as they are in mathematics. The only exception is the correct use in the case of forces as vectors. The Coulombian model of electric force is familiar to the students, so it was used as the basis when introducing the field model. Secondly, the meaningful use of graphical representation was found to be troublesome. Force vector addition was used to summarize the forces on the charge (charge B). Some students, however, drew the repulsive force vector in such a way that it ended at charge B rather than originating from it. In the case of attractive force, the force vector originated correctly from charge

B, leading to a confused graphical representation of the forces, as shown in Figure 14.

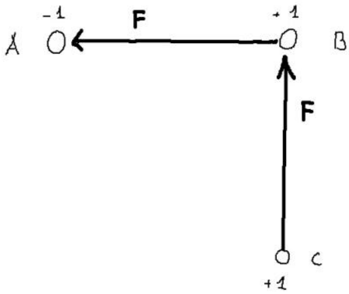


Figure 14. Students' (Number 2 and Number 4) representation of Coulombian forces acting on charge B.

5.2.3 Article 3 results

Article 3 deals with ways to increase the students' comprehension of electrostatics and especially Gauss's law. This depends on understanding the concept of an electric field. In this article, we applied the method of Educational Reconstruction in order to devise more effective teaching. The general idea of the reconstructed electrostatic theory is to introduce the first four steps of electrostatics and their dependence in increasing hierarchical order: Step 1, electric force (Coulombian force); Step 2, Coulombian electric field; Step 3, electric flux; and Step 4, Gauss's law (and Maxwell's electric field).

These steps are arranged in this sequence in most university textbooks. From a pedagogical perspective, however, the significance of the four steps is that they represent a deeper understanding of the relation between force and field. In addition, it is important for the learner to understand how the field is derived from the force, and how the force and field are connected to each other. The concept of flux depends on the concept of electric field and surface, both treated as vectors. Furthermore, it is important for the learner to understand the relationship between the total electric flux through a closed surface and the enclosed charges, all of which form the conceptual basis for Gauss's law. The mathematical representation of Gauss's law is meaningful only if the preceding concepts are understood correctly.

Analysis of the final exam questions showed that some students still had problems concerning the essence of a physical vector. Nevertheless, in light of our experience the large number of acceptable responses to the second exam question testified to maturation in the students' understanding of Gauss's law and their ability to use it correctly. The key issues were the requirement to master new mathematical techniques, simultaneous learning of new physical concepts, and the shift from understanding electric force to the active use of electric field. The course on basic electromagnetics includes many new physics concepts, such as Gauss's law, that are not taught at the secondary level, so students are unfamiliar with the elements (*i.e.* field, flux, and surface integration). Due to the high degree of abstractions, the physical theory of electrostatics needs revision from learning and teaching perspective.

Educational Reconstruction provides a frame in which new instruction can be developed in a way that expands and interconnects the essential concepts into a clearer form that simplifies the theory concerned. To sum up our analysis of the effectiveness of the instructional intervention, there are indications that a large proportion of the students applied a correct understanding of electric force, electric field, and Gauss's law. In addition, it was found that a good comprehension of Gauss's law, and thus a theoretically more powerful concept of electric field, seems to provide a better background for subsequently studying subjects such as electric potential, capacitance, and current when they are introduced at the university level as an outcome from the interpretation of electric field. The efforts made to understand Gauss's Law and the formation and physical meaning of the surface integral also provide a good background for learning the other Maxwell's Equations. In practice, the analogies between Maxwell's Equations are exploited: the left-hand side of the equations contains the flux or path integration containing the vector field and referring topology, while the Right-hand side of the equation can be seen as a (net) source to that field. This idea is repeated in all of Maxwell's Equations. If Gauss's Law is learned and well understood at the beginning of the course, it definitely is beneficial in learning the other Maxwell's Equations.

5.2.4 Article 4 results

The fourth and fifth articles go through the same schematic procedure as the three previous ones. The domain of these articles is the basic concepts and teaching intervention concerning magnetic force and magnetic field. Article 4 reports the students' conceptions of these issues. The study reported in this article provides an empirical context for developing instruction in magnetostatics in the introductory university course in electromagnetics that was reported in the fifth article. Our findings show that students do not produce coherent explanations for magnetic field and force. Furthermore, understanding the use and basis of the specific Right -hand rules for the magnetic field and force are challenging for students since they do not possess a proper physical foundation for those rules. Typically, the students tend to explain magnetic phenomena using an incorrect analogy related to electrical phenomena. In addition, the students' reasoning behind the Right -hand rules in magnetostatics is remarkably vague. Our results reveal that the Right -hand rules learned at the upper secondary level did not offer sufficient theoretical background for understanding the rules properly. In addition, no emphasis is placed on the vector character of the fields by the students. The application of Right -hand rules gives relatively good results in solving problems that are highly symmetrical and simple. However, the simple rules seem like memorized instructions from a cookbook. They have limited power in problem solving or in explaining magnetic phenomena. If used correctly, however, the rules are helpful in providing suggestive directions for force and field. By themselves, they are insufficient for replacing the original vectors. The rules are also difficult to remember, since the relevant scalar relations are not strongly linked.

The results reported in this article suggest that the teaching of electromagnetics should be modified. Based on our results, instruction at university level needs to start by reviewing the underlying principles of magnetostatics, starting from the level taught at the upper secondary school. In particular, the basic features of magnetic force and field should be reconsidered by the instructor. We found no coherent competitive or alternative misconceptions that would be an obstacle to the proper learning of the appropriate model of magnetostatics. The faulty analogues to an electric field and force are vague and incoherent. They simply fulfill the students' need to have some kind of explanation rather than nothing at all. The challenge is to provide instruction that results in a clear understanding and a passion to continue learning.

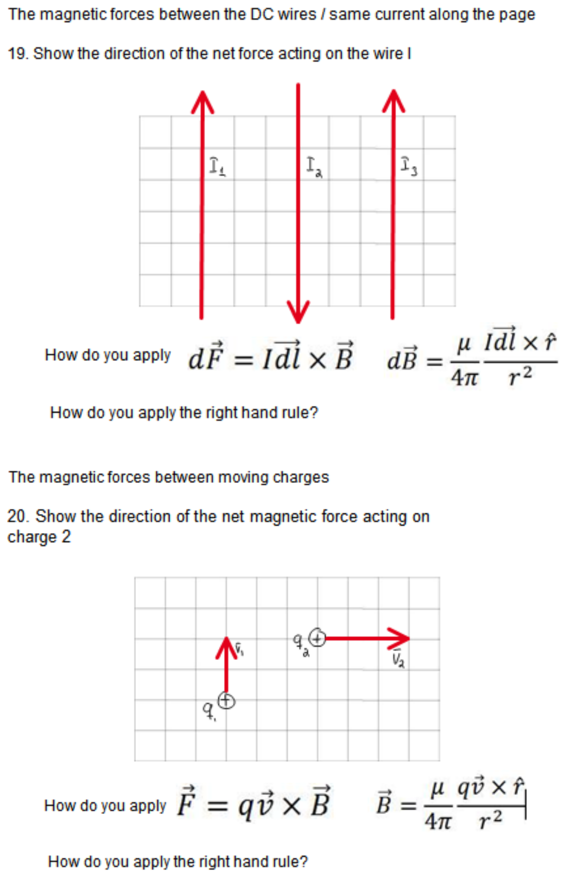
The main implication of this study for the teaching sequence is that there is a need to strengthen vector thinking and the physical interpretation of Biot-Savart's Law and the law of magnetic force.

5.2.5. Article 5 results

In the fifth and last article of this thesis, we used students' conceptions of magnetic field and force to design a teaching sequence. The model of Educational Reconstruction was used to develop a teaching sequence in university magnetostatics to help students learn the concepts of magnetic field and force. The basis of magnetostatics rests on the concepts of field and force as represented in Biot-Savart's Law and the law of magnetic force. In addition, the non-conservative character in both arises from the vector cross-products, which in turn are essential for an understanding of 3-dimensional representations of the referring relations. Equally important are the interconnections between a mathematical understanding of the relationship and their graphical representation. When linked together correctly, these result in a correct use of the referring Right -hand rules. The main aim in reconstructing the teaching of Biot-Savart's Law and the magnetic force law is to provide students with vector-formed relations that can be used as active tools for thinking, explaining, and problem solving.

A well developed teaching sequence with novel multi-step tasks was implemented, and student learning was monitored. The results indicate that the students reached the learning goals after implementation of the teaching sequence, and some typical misconceptions could be avoided. In addition, the students learned to use vector relations as a powerful method to support their thinking and in problem solving in magnetostatics.

The outcome of the instructional intervention was that students were able to understand a concept once they know how to apply the correct method. They understand in a general and coherent way, enabling them to abandon their initial concepts. The most important addition to what the students had previously learned and the key to their understanding of further topics in the course on electromagnetics was the introduction of the concept of vectors. The implication for further research is that the students' performance following instruction should be measured with more challenging test examples. After all, we expect students to learn more effective methods in the process of learning physics and to more profoundly understand the topics that they learned previously. Figure 15 illustrates one lecture task. The aim of this task was to invite the students to use both Right -hand rule and its relations with cross products in reasonable ways. The Right -hand rule is not applicable in all situations, i.e. it is non-orthogonal. However, it is useful in supporting the reasoning based on the use of the respective vector tools.



The magnetic forces between the DC wires / same current along the page

19. Show the direction of the net force acting on the wire I

How do you apply $d\vec{F} = I\vec{dl} \times \vec{B}$ $\quad d\vec{B} = \frac{\mu}{4\pi}\frac{I\vec{dl} \times \hat{r}}{r^2}$

How do you apply the right hand rule?

The magnetic forces between moving charges

20. Show the direction of the net magnetic force acting on charge 2

How do you apply $\vec{F} = q\vec{v} \times \vec{B}$ $\quad \vec{B} = \frac{\mu}{4\pi}\frac{q\vec{v} \times \hat{r}}{r^2}$

How do you apply the right hand rule?

Figure 15. *Comparing the methods of using the Right -hand rule and vector relations.*

The chapters dealing with the fundamentals of magnetostatics are followed by chapters dealing with topics such as Ampere's

Law, inductance, and electromagnetic induction. Successful learning of these topics depends on the quality of instruction on the phenomena and the principles of magnetostatics. We were primarily influenced by the students' vague understanding of the conceptual, graphical, and mathematical representations of a magnetic field as a vector field.

It seems that Educational Reconstruction is a suitable method for making use of recognized learning difficulties, the physical content, and the aims of the instruction in developing effective teaching in physics.

6 Discussion

6.1 CONTRIBUTION TO SCIENCE DISCOURSE

The development of the electromagnetic field theory by Maxwell and Heaviside was an outcome of a troublesome process. The field-related model developed gradually from Faraday's Lines of force concept to Maxwell's formulations of the field equations and through Hertz's experimental confirmation of the existence of electromagnetic waves predicted by Maxwell. Although the mathematical form developed by Heaviside (Heaviside, 1893) is the one that is recognized today as Maxwell's equations, these remained unknown to the majority of the science community until the early 20th century. Nevertheless, the concepts of the electric and magnetic field were found and expressed in a compact form with the highest theoretical power. The electric and magnetic phenomena explained with the concept of the field is a new ontological category that differs from the Newtonian categories in terms of "action at distance", an idea which still causes confusion among students (Furio & Guisasola, Difficulties in Learning the Concept of Electric field, 1998). Due to the high degree of abstraction and simultaneous demand for university mathematics it is not surprising that undergraduate students have difficulties when confronted with modern electromagnetic theory, both at the conceptual level and in solving problems (Bagno & Eylon, 1997)(Dunn & Barnabel, 2000). The students confuse the electric force and electric field, and also use a false analogy between electric and magnetic fields and forces (Guisasola J. , 2004). Although there are examples(Chabay & Sherwood, 2006) of making the learning curve more gentle for undergraduate students in introductory courses on electromagnetics, it is the contention of this study that the field concept is the most explanatory and powerful concept and should be found behind the electricity-related topics of potential, current, capacity and energy.

The following sections present the theoretical and practical implications of the new contribution concerning the steps in electro- and magnetostatics.

6.2 THEORETICAL IMPLICATIONS

6.2.1 The electric field

Previous instructional approaches in teaching electric field concepts were developed mainly for the secondary level. Furio reported an activity that included several tasks in the following categories (Furio & Guisasola, 2003):

First part: New invisible forces with an extraordinary power.
1. Electric nature of matter.
2. A quantitative study of the forces between electric charges that are not in motion.
3. New questions cast by the electric knowledge reached.

Second part: A general interpretation of electric interactions, the electric field.
4. The electric field. What is the electric field? A qualitative idea of the electric field created by a charged system through problem situations.
5. Practical problems that the electric field concept can solve.
6. An energetic interpretation of electric field.
7. New questions cast by the knowledge reached that gives rise to new studies.

These activities represent the possibilities that are present when teaching introductory electromagnetics at the secondary level (Furio & Guisasola, 2003). In contrast, this research project aimed at developing the field concept more precisely at the university level. In short, the instructional procedure can be expressed in terms of the *steps* that resulted from the Educational Reconstruction process. In contrast, the goal of this research project was to teach the field concept in a more precise way to students at the university level. The steps are as follows:

1. Establishing the basis of the Coulombian field concept of electric force.
2. Differentiation between field intensity and electric force.
3. Enhancing the vector character of ***E*** and the concept of electric flux.
4. Justifying the demand for the field concept.

These *steps* represent a more precise fine-grained development of the instruction to deal with the learning difficulties that have been identified in previous studies and in this one.

The concepts of electric and magnetic fields and forces are quite abstract and cannot be arrived without formal instruction. Learning about electric phenomena often starts by observing the interaction of charged objects excreting repulsive or attractive forces to each other (Young & Freedman, 2008). Thus, the force concept that is familiar to the students from their previous instruction in mechanics can be applied in the context of electric charges. This requires the learner to transfer the knowledge of the mechanical force into a new context. Although there is a mechanical field analogue to the electrical one, the gravitational field is introduced to this extent later than the electrical field in the physics curriculum at the university level. This actually leads to a situation where the learner develops later and compares the gravitational field, potential and energy concepts based on the learning experiences concerning electrical field concepts. Hence, the formation and the accuracy of the electric and magnetic field concepts create the basis of the general field concepts that are taught later. The instruction in electromagnetics at the university level begins with studies of the static charged particles excreting electric forces to each other. In this phase the students are invited to form the abstraction, the electric field, from the more concrete concept of the electric force. At the secondary level the electric potential, resistance, current, capacity, and energy are introduced as separate tools to be applied to problems. At the university level, these issues are revisited by revealing a new layer beneath the surface: the field theory that unifies the separate topics by showing the concept of the electric field. Soon thereafter, the electric field concept and Gauss's law is introduced. A good comprehension of Gauss's law, and thus a theoretically more powerful concept of electric field, provides a better background for subsequently studying electric potential, capacitance, and current when they are introduced at university level as an outcome from the interpretation of electric field. This can be seen in the treatment and order of topics in university textbooks (Young & Freedman, 2008)(Knight, 2004)(Cutnell & Johnson, 2007)(Giancoli, 2009)(Halliday, Resnick, & Walker, 2011)(Ohanian, 1988). Analogously, understanding the force concept, force as a vector and force as described in Newton's Laws, force plays an essential role in understanding the concepts of inertia, kinetic energy, and collisions. Thus, efforts made to understand Gauss's law and the formation and physical meaning of the surface integral also provide a good background for learning the other Maxwell's equations. However, Chabay's analysis of the learning problems connected with Gauss's law suggests that there is a need to restructure the sequence of the introductory course in such a way that Gauss's law is introduced later in the course (Chabay & Sherwood, 2006). This would be an understandable choice, also from a teacher's perspective, since Gauss's law is difficult for students if presented in the initial stage of a course. The approach in this study is based on teaching the concepts in carefully planned steps. The steps that include electric field and Gauss's Law are presented at the start of the course. This takes more time as a result of working through the various steps, but results in less instructional time later. Understanding the electric field really is essential to making sense of the content of electric potential, capacitance, and current.

6.2.2 The magnetic field

There has been less research on students’ concepts of magnetism than on their concepts of electricity. Everyday magnetic phenomena such as attraction and repulsion are explained by erroneous electrical analogues (Guisasola J. , Almudi, Salinas, Zuza, & Mikel, 2008). The students’ explanations of magnetic field and force give the impression that they are actually speaking about electricity, for lack of a better model (Saarelainen, Hirvonen, & Laaksonen, 2007)(Guisasola J. , 2004). Electricity is so closely attached to magnetism that students believe that a permanent magnet exerts forces on a static charge in close proximity (Maloney, 1985). Both the concepts of electricity and magnetism have been investigated, resulting in base line performance tests such as CSEM (Maloney, O'Kuma, Hieggelge, & Van Heuvelen, 2001). However, the typical test questions concerning the electric and magnetic field are given in highly symmetrical situations. In the case of the magnetic field, the symmetry (the right angle between the velocity and the field or between the velocity and the observer) encourages the students to use the Right -hand rules. This in turn has been found to be problematic when it comes to getting information on how students really understand the three-dimensional vector character of the field, and the cross-product within the relations. Only a few instructional approaches are applied in teaching magnetostatics at the university level. The closest one to the domain of this research report is Guisasola’s’ approach (Guisasola & Almudi, 2009).

The emphasis in their approach was on:
1. How a magnet works
2. The relationship between the magnetic field sources (bar magnet/solenoid)
3. What magnetic fields act on?
4. Magnetic field sources
5. Confusion between field and force
6. Confusion between electrical and magnetic effects
7. Relativity of the magnetic field

However, Guisasola's approach did not focus on building the basis of the comprehension of the magnetic field and force, i.e. the detailed physical interpretation of how and under which circumstances the field is generated and how the force acts on an object. These questions demand the use and understanding of field vectors and the respective relations of Lorenz's force law and Biot-Savart's law with the cross-productions. The new idea in the research was to introduce the *steps* towards the essential conceptual and qualitative understanding of the basic relations:
1. Magnetic field (Biot-Savart law)
2. Magnetic field topology
3. Magnetic force
4. Representation of the force

The magnetic field concept is being built upon the electrical one by recognizing the similarities and differences. Results of previous studies show that students confuse the concepts of electric and magnetic fields(Furio & Guisasola, 1998) (Saarelainen, Hirvonen, & Laaksonen, 2007). The behavior of the magnetic field, in many cases, does not differ from that of the electrical field. The basic attractive or repulsive forces with bar magnets are understood as being analogous to the attractive and repulsive forces between charged particles. In addition, the formation and topology of the magnetic field are difficult to perceive due to the interpretation of the three-dimensional vector cross product (Saarelainen, Hirvonen, & Laaksonen, 2007)(Saglam & Millar, 2006) (Guisasola J. , Almudi, Salinas, Zuza, & Mikel, 2008). The pre-instructional models of the Right -hand rules are useful at the university level only if they are based on the interpretation of the vector cross products. However, the rules of thumb are, unfortunately, quite often memorized as if they were cook-book instructions without physical meaning, and applied either too narrowly or too widely. The result is a student who uses the Right -hand rule only in situations related to the examples that are introduced. Learners replace the magnetic field with an electric field analogue in all cases, and have no other model to use. To be able to follow the traditional course of instruction in electromagnetism at university level, students should have a solid grasp of the concepts of magnetic field and force. They should be able to use the vector-based relations concerned with magnetic field and force in addition to having mastered the vector cross product and its interpretation. In reality, however, this requirement proves to be too demanding due to varying levels of instruction at the secondary level. Thus, the majority of the students still have incorrect concepts or flaws in their thinking that prove to be obstacles when they attempt to follow the traditional university-level courses, as explained in the review of previous studies. Clearly, the main obstacle to the students' learning about magnetic field and force is their vague grasp of the concept of field and especially of the relevant vector relations. One aspect of the theoretical implications of this research report is the novel use of educational reconstruction. This is not commonly used at the university level, and almost never in the case of electro- and magnetostatics, as was done in this study. The physics content were not simplified, but the sequence and emphasis within the taught sequence was made more accessible and understandable for the student. The main finding in this research is that understanding the vector character of the fields is essential in learning about electro- and magnetostatics. Furthermore, by using the framework of educational reconstruction it is possible to analyse the content, to take the results of previous research into account, and to add the instructors' insight to the coherent and logical outcome of new instruction. The effectiveness of the instruction was measured and compared with the educational objectives, also within the frame of educational reconstruction.

6.3 PRACTICAL IMPLICATIONS

6.3.1 The electric field

Another aim of this research was to create an instructional approach and material that would help students to overcome their learning difficulties. The method of educational reconstruction that was used here was developed to produce and evaluate more effective instruction in accordance with scientific inquiry. The practical implications for teaching the basics of electro- and magnetostatics can be found in Articles 3 and 5. The requirement to master new mathematical techniques and to simultaneously learn new physical concepts seems to be difficult for students. Shifting from understanding electric force to the active use of electric field is not a straightforward process for most students (Dunn & Barnabel, 2000). By taking into account the students' preconceptions and learning problems, and an analysis of the subject taught, it is possible to design a good foundation for an instructional intervention (Furio & Guisasola, 2003). The physical theory of electrostatics is quite abstract and it is generally presented in a compact form. Thus, it provides space for educational reconstruction that expands and interconnects the essential concepts into a clearer form that reduces or simplifies the theory. In practice, the idea of forming, enhancing, and justifying the vector concept becomes concrete to a student when they take the four steps of source, force, field and interpretation of Gauss's law. One example of doing so is going through the set of tasks given in the appendix to Article 3. For example, there the electric field becomes familiar as a three-dimensional vector field when examined in various situations that are not always symmetrical.

During the intervention of the teaching methods, *e.g.* group discussions, the interplay between the students and their instructor was emphasized. The consensus reached during these discussions proved to correspond to the scientific aims of the teaching. The discussions also helped the instructor to see what the students had learned and to identify which topics were the most difficult ones for them to understand.

6.3.2 The Magnetic field

The instructional approach that was used to teach magnetic field focused on the basic concept of the magnetic force law and Biot-Savart's law. Understanding the Right -hand rules that are attached to these laws became an important aspect. Since instruction at the upper secondary level on the magnetic forces and fields is not based on a deep analysis of the vector cross product, the rules of thumb are given a weighty role. However, the rules themselves without a physical foundation do not represent physical understanding. Thus, the aim of the instruction was focused on improving the students' adoption of the desired scientific model of magnetism and to promote their problem-solving skills (Nguyen & Meltzer, 2003)(Guisasola J. , 2004). In practice, we took into account the aims of the instruction, the students' initial knowledge, and the theoretical nodal points in physics theory that are relevant to the task of bridging the gap between students' conceptions and scientific models. More specifically, special attention was paid in designing the project to the meaningful physical interpretation of the vector cross-products within the relations of Biot-Savart's law and the magnetic force law. The design of the teaching sequence was based on the Educational Reconstruction method. The practical implementation of the reconstructed instruction consists of a set of 20 multi-step tasks and problems, which are presented in detail in Appendix A of Article 5. The main aim was to introduce, enhance, and justify the vector character of the magnetic force and field. More precisely, the vector cross product within the magnetic force law and Biot-Savart's law was dealt with in detail. The main idea underlying the development of the instruction was a desire to emphasize the essential role played by the 3-dimensional interpretation of the vector cross-product. Hence, in a mathematics course that was taught alongside this course in magnetostatics, students were introduced to the notion of the vector cross-product as a mathematical tool. They had had no previous experience, however, of applying the method in the physical context of magnetostatics. Once the notion of the vector cross-product with graphical representations of field and force had been introduced, the Right -hand rules could be applied. This teaching sequence ensures that students understand both the origin of the rules and the area in which the rules can be applied.

Consequently, the idea of the cross product was attached directly to the Right -hand rules, and the students were shown the limitations of the rule which restricted the orthogonal vector examples. Furthermore, the steps included a task analyzing the usefulness of using vectors and rules.

6.4 TRUSTWORTHINESS

Qualitative analysis produces a different type of knowledge than quantitative inquiry. The nature of the paradigm explains the difference. In a positivist paradigm that could be applied in empirical sciences such as physics, the hypotheses and research questions are set in advance and their validity measured under controlled circumstances(Guba, 1990)(Guba & Lincoln, 2005). Reliability is the consistency of measurements or the estimation to which the measurement can be repeated under the same circumstances. Validity deals with the accuracy of the measurement (Thyler, 2001). Thus, validity is more important than reliability, since no matter how reliable the instrument, it is useless if it measures wrong or inappropriate issues.

In quantitative research, the aims of inquiry are to identify causal determination, prediction, and generalisability of findings. In qualitative research, the aims are to seek illumination, understanding, and extrapolation to similar situations (Hoepfl, 1997).

In this work, the subjects under inquiry were the students, the learning process, and the aims of instruction. The stage is set from actors, the people participating in the teaching, who are conscious and intentional, and whose behavior depends on their ideas and the meanings they attach to the world (Miles & Huberman, 1994). This stage with its multiple perspectives is seen in this work under the constructivist view, and the methods used are the result of interpretation of written tests, content analysis, interviews, and observations. The results can be described as the increased awareness of the students' potentials, understanding the advantages of different approaches in instruction and evaluating the learning process in relation to the aims of the instruction. Quality matters in qualitative research, but the attributes of validity and of *reliability* attached to quantitative research do not seem adequate to describe the variety of aspects that are present in qualitative research (Seale, 1999). An alternative four-item criterion of trustworthiness for constructivist research has been presented by Lincoln and Guba (Lincoln & Guba, 1985). Trustworthiness criteria are defined as credibility, transferability, dependability, and confirmability. These issues are discussed in more detail below, using the interpretation of Pickard and Dixon and with reference to this research (Picard & Dixon, 2004).

6.4.1 Credibility

"Credibility is shown by prolonged engagement with the research participants, persistent observation of those participants, triangulation of the techniques used to study those participants, their contexts, peer debriefing, and member checks. Member checking is a vital part of a constructivist inquiry. In order to check with the actors who are the subjects of the research one must focus on how they interpret the researchers' interpretations" (Picard & Dixon, 2004).

In this research the inquiry was carried out by the instructor. During the past eight years attention has been continuously paid by the instructor to the physics to be taught, success in instruction, and success in learning. At the same time I as the researcher/teacher had the responsibility of a tutor for the majority of the students through the years. The duties have involved giving advice to each student in addition the researcher/teacher has observed the students' performance in electromagnetics during earlier studies of the same topics. It was possible to follow the students studying electromagnetics for several years. This period provided insight on what eventually works in teaching physics. It can be said that the researcher/teacher must be deeply committed to becoming an expert in understanding the field of research and the research participants – the students – vertically; different students in the same course annually and horizontally; and the same students in different courses over an extended time period.

This research utilized the methods of written tests and interviews. Educational reconstruction served as the general framework of the research into which the empirical data and designed instruction were placed in accordance with the aims of the inquiry. The written tests were based on the CSEM and BEMA tests, both of which are widely used for probing base line performance in undergraduate electromagnetics. The credibility of the CSEM test and its suitability for testing the issues in this study has been proven in previous studies (Kohlmyer & Caballero, 2009).

The interviews served as a triangulation to the written tests (Denzin & Lincoln, 2003). Based on the test results, a group of students from the whole cohort were invited to take part in videotaped interviews. The students chosen were physics majors of both genders, and they performed medium score at the CSEM and BEMA tests. In the interviews the students were asked to explain the reasoning behind their answers to the CSEM test questions. Given the context of the physics problems, it was assumed that the students actually expressed their own ideas and reasoning. The presence of the teacher at the individual interview situation did not seem to be a problem for the students. After a short description of the whole situation, the students relaxed and started the conversation quite naturally. The fact that physics was the topic shifted the focus of the discussion away from personal opinions, and made it possible to analyze the students' answers, and to identify categories reflecting similar thoughts and elements in their responses. Typically, physics problems are objective enough so that students do not try to please the instructor by saying what they think is expected, simply because they do not know what that is. Rather the students try to use their own thinking. Member checking was included in the interviews. The interview started by reading the students' written answers and having a discussion about it. The interview questions were based on the same questions as on the test. This was done to gain more detailed information on the students' thinking rather than triangulation. The results from the interview confirmed the initial assumptions of the researcher and revealed new ideas as well. After the interview, the researcher and the student had a discussion on the issues in the interview questions. During this exchange the researcher asked the student whether the teachers impression of the students' thinking, based on the student's answers, were correct. In addition, the interview questions served as individual goals of the learning for the student, e.g. the identified learning difficulties were addressed and possible solutions were discussed. This represented an example of what Guba means by member checking, which clearly is "the most crucial technique for establishing credibility" (Lincoln & Guba, 1985).

All the main methods, findings, and conclusions have been reported in the peer reviewed papers, so the peer review requirement has been fulfilled.

6.4.2 Transferability

'The trouble with generalizations is that they don't apply to particulars.' (Lincoln & Guba, 1985) . In constructivist inquiry, the goal is to allow for the transferability of the findings rather than wholesale generalization of those findings. Here the researcher provides 'rich pictures' on an individual level, and the reader then gathers, or already has, empirical evidence concerning the cases to which they wish to apply the findings".

In this research the subjects under inquiry were the students'preconceptions, the sequenced conclusions and thereconstructed teaching sequence. The intention was to describe the students' conceptions as diversely and profoundly as reasonable in light of the aims of the inquiry. Since the authentic teaching sequence comes from the participation of individual actors – the teacher and the students – the individual students always give unique responses to teaching. It can be said that exactly the same procedure in instruction never produces exactly the same learning result even for the same instructor. One has to actively listen to the audience and sense their presence in every learning situation. During the interviews the students were encouraged to speak about how they arrived at specific conclusions and how they decided to use drawings to support their narrative. Together with their written test answers and the solutions in the final exams, the students' conceptions and performance were judged with respect to the desired aims of the instruction. The results in this study provide guidance for structuring, emphasizing, reconstructing, and understanding the weaknesses and strengths of the students' conceptions that yield improved learning outcomes. Teachers must keep in mind the initial conditions and the conclusions of this study when applying the guidelines in their particular situations.

I have endeavored to describe all the essential elements of the "rich picture" of the investigation. However, there are many ideas, learning materials, results, and notes that were gathered during the many years of teaching the course which have not been referred to here. Some of these items were omitted in order to keep the articles short and focused.

6.4.3 Dependability

"Dependability is established by the 'inquiry audit', and the external 'auditor' is asked to examine the inquiry process, the way in which the research was carried out. In order to allow for this an audit trail has to be maintained by the researcher along with his/her own research journal (Schwandt & Halpen, Linking auditing and metaevaluation: enhancing quality in applied research., 1988). There is also the task of examining the data produced by the research in terms of accuracy relating to transcripts and levels of saturation in the document collection".

This research report consists of five peer reviewed journal or proceedings articles. Thus, the requirement of an inquiry audit is fulfilled. Concerning the interviews, the student who were invited to take part were informed that no advance preparations were necessary. In addition, the pre-interviews took place at the beginning of the course so that there were no significant "tuning in" for the subject under consideration. However, it was noteworthy that the interview situation itself was interesting for most of the students and they tended to go back to correct their answers to the previous questions as the interview went along. This made it sometimes difficult to answer the question about the initial condition of the student regarding the given interview question. The post-interviews, post-tests, and the final exam questions were intended to measure the responses to the instructional intervention. At this stage in the course the students had learned the taught issues independently, had participated in the weekly problem solving /homework, and performed and had prepared the solutions with peers, as advised by the instructor. Thus the evidence of improved teaching and the power of using the educational reconstruction can be questioned to some extent.

6.4.4 Confirmability

"Confirmability is vital in terms of limiting investigator as far as it is possible to go from the stand point of not only accepting subjectivity, but using it as a research tool. The notion of objectivity is still often used in post-positivist, qualitative research but it is becoming increasingly more difficult to defend even in the modified form in which it is now applied. The notion that there is a way of studying human behavior which can generate objective results is rejected by constructivist epistemology. The alternative is to ensure that the results, accepted as the subjective knowledge of the researcher, can be traced back to the raw data of the research, that they are not merely a product of the 'observer's worldview, disciplinary assumptions, theoretical proclivities and research interests'. This is done by using an audit trail, which provides a means of ensuring that constructions can be seen to have emerged directly from the data, thereby confirming the research findings and grounding them in the evidence (Charmaz, 1995)(Schwandt & Halpen, 1988)."

Depending on the philosophical nature of the paradigm used, quantitative researchers try to show that they have avoided regarding the interpretation as arising from the data, whereas qualitative researchers underline their involvement in the process of inquiry. In the present investigation the presence of the inquirer is justified by the fact that students' thinking is constantly changing, and the inquirer should be there to witness, observe, and record the situations before and after the change (Patton, Enhancing the Quality and Credibility of Qualitative Analysis, 1999)(Patton, 1990). Due to the inquirer's interpretation of the students' responses, it is not always a straightforward process to trace the conclusions back to the raw data. While for quantitative researchers it is important to describe the accuracy and suitability of the instrument, the qualitative researcher is the instrument. Therefore, it is important to describe the background and motivation of the researcher as a part of the interpretation of the research results. The trustworthiness and agreement of the reader also depends on how well this is done. This study consists of both inquiries on undergraduate students' conceptions of electromagnetics and the instructional intervention to overcome identified learning difficulties. Therefore, it is quite natural that the researcher was also the instructor. Having another person as an instructor would have been troublesome in many ways. It would have been similar to a surgeon giving orders from one end of the operating room to a colleague at the other end on how to perform an operation.

Creating the written tests and the interviews was critical when designing a new approach for the lessons. The students' answers revealed significant flaws both in their thinking and their concepts concerning electric and magnetic fields, forces, and sources. The students were capable of using their own thinking in a creative way and utilizing the new concepts, which gave the instructor the courage to challenge the students to confront difficult topics during the reconstructed instruction. This is an example of confirmability as described by Patton (Patton, 1999), concerning how the inquirer is actively involved in the research situation. However, the researcher should recognise his/her role and include it in the frame of the research rather than trying to be isolated from it.

6.5 RECOMMENDATIONS FOR FURTHER RESEARCH

This research project aimed at improving the instruction of electro- and magnetostatics. More precisely, the focus was on constructing an appropriate understanding of electric and magnetic fields as vector fields. Another aim was to use the field concepts as an explanatory basis and reasoning behind the relations of the electric and magnetic fields and forces. In the case of the electric field, the use of the concept was applied in the generalized relation of Coulombian force, i.e. Coulombian field and Gauss's law. The magnetic field concept was applied in the cases of the magnetic force and field relations. It would be quite natural to continue the inquiry with the topics of Ampere's law and Faraday's law, since the rest of Maxwell's equations are field dependent and treated similarly as Gauss's law. There are a few studies dealing with electromagnetic induction (Thong & Gunstone, 2008)(Galili, Kaplan, & Lehavi, 2006)(Mauk & Hingley, 2005). The common feature of Maxwell's equations is that on one side of the equation there are source terms and on the other there are vector fields as a part of the integrands inside the flux and path integrals. Learning about Ampere's law and Faraday's law would require a similar process of establishing, enhancing and justifying the presence and meaning of the vector-formed electric and magnetic fields as that used in the present research. The similarity between the difficulties in learning Maxwell's equations has also been noted by Guisasola and colleagues (Guisasola J. , Almudi, Salinas, Zuza, & Mikel, 2008).

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MARKKU SAARELAINEN

Teaching and Learning of Electric and Magnetic Fields at the University Level

Electromagnetic field theory forms an essential basis in the physics curriculum and in the physicist's professional competence. The basic problem in teaching at the undergraduate level is that the abstract formulation of electromagnetism is a result of theoretical evolution in physics and thus difficult to comprehend. This dissertation aims to develop and evaluate effective instruction for the basic course on electromagnetism. More specifically, it focuses on the concepts of electric and magnetic fields and forces.

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