Developing instruction in magnetostatics at undergraduate level
Part 1 Undergraduate students' initial knowledge of magnetic field and magnetic force

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Abstract

This study explores first-year university students' understanding of magnetic field and force. Students' conceptions were investigated by means of a written test (N=38), and a sample of students (N=7) participated in a semi-structured interview. According to our findings, students do not produce coherent explanations for magnetic field and force. Furthermore, understanding the use and the basis of the specific Right-Hand Rules for the magnetic field and force is challenging for students since they do not possess a proper physical foundation for those rules. Typically, the students tend to explain the magnetic phenomena by using an incorrect analogy related to electrical phenomena. In addition, the reasoning behind the Right-Hand Rules in magnetostatics is remarkably vague. The study introduced in this article provides an empirical context for developing instruction in magnetostatics in the introductory university course in electromagnetics that will be reported in Part 2.

Keywords: Undergraduate, electromagnetics, magnetic field concept.

Resumen

Este estudio explora la comprensión de los estudiantes del campo magnético y la fuerza del primer-año de universidad. Las concepciones de los alumnos fueron investigadas por medio de una prueba escrita (N=38), y una muestra de estudiantes (N=7), participaron en una entrevista semi-estructurada. Según nuestros resultados, los estudiantes no producen explicaciones coherentes para el campo magnético y la fuerza. Por otra parte, comprendiendo que el uso y la base de las especificaciones de las Reglas de la Mano-Derecha para el campo magnético y la fuerza es un reto para los estudiantes, ya que no poseen una base física adecuada para esas reglas. Por lo general, los estudiantes tienden a explicar los fenómenos magnéticos mediante el uso de una analogía incorrecta en relación con los fenómenos eléctricos. Además, el razonamiento detrás de las Reglas de la Mano-Derecha en magnetostática es muy vaga. El estudio presentado en este artículo proporciona un contexto empírico para el desarrollo de la instrucción en magnetostática en el curso universitario de introducción al electromagnetismo que se presenta en la Parte 2.

Palabras clave: Licenciatura, electromagnetismo, concepto de campo magnético.

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I. INTRODUCTION

Maxwell's four known equations form the kernel of electromagnetic field theory. Although superior and theoretically highly powerful, Maxwell's equations are difficult for first-year university students to learn [1]. This difficulty arises from the vector character of the electric and magnetic fields [2, 3]. Indeed, the treatment of Maxwell's equations has been conducted using new conceptual tools in physics such as electric and magnetic vector fields, surface vectors, and path vectors, and also by referring to a new mathematical treatment such as flux and path integrals and using a physical interpretation. In general, an adequate treatment of Maxwell's equations requires a student simultaneously to use new concepts in physics that involve new mathematics. The use of such mathematics in a physical context is also known to be difficult [4, 5]. Hence, before embarking on the use of Maxwell's' equations in the teaching of magnetostatics, it is essential to understand the basic relations that exist between Biot-Savart and the magnetic force laws dealing with magnetic field and magnetic force.

Magnetism, on the other hand, is an everyday phenomenon for students who are familiar with the basic attractive or repulsive forces between two magnets. Static charges and magnets resemble each other closely in behaviour and have thus given rise to a common misconception: the reasons for magnetic interactions are misinterpreted as analogs to their electrical equivalents [2] [1]. The false electrical analogue is also the most populated category in Guisasola's classification of students' descriptions of magnetism [6].

Although the electric and magnetic interactions are different in nature, the conceptions associated with them do have features in common. In both cases, students' confuse field and force, and this leads them to understand magnetic force as a moving charge that is the equivalent of magnetic field, or at least that both the force and the field point in the same direction [2]. In the case of electric field and force this is not the worst starting point, since the field and the force are parallel and the field can be derived and defined from the force. Magnetic interactions –magnetic force – cannot, however, be considered without taking into account the movement of the charge in the presence of the non-parallel magnetic field. Thus, the formation of the field concept is not derivable from the force concept as is the case with electric field [7].

The Biot-Savart law, which is theoretically inferior to Ampere's law but is nevertheless, in many cases, a more practical and simpler description, can be considered a starting point where magnetic field **B** is computed as a result of moving charge q or the current element ***Idl***, as shown, below, given in Eq. 1.

$$d\vec{B} = \frac{\mu}{4\pi}\frac{I\vec{dl}\times\vec{R}}{R^3}, \text{ or } d\vec{B} = \frac{\mu}{4\pi}\frac{q\vec{v}\times\vec{R}}{R^3}. \qquad (1)$$

The Biot-Savart law for a current element and a moving charge. The vector R is pointing from the element or a charge towards the point of observation.

Both Biot-Savart law and Ampere's law include the idea of orthogonality between the direction of the current and the direction of the field. The Biot-Savart law defines this more explicitly by stating the resultant magnetic field vector as proportional to the cross-product of an oriented wire segment and the position vectors. Magnetic force, on the other hand, is a cross-product of the current element and the magnetic field – again causing the force and field to be perpendicular. The law of magnetic force can be expressed as in Eq. 2:

$$\vec{F} = q\vec{v}\times\vec{B} \text{ or } d\vec{F} = I\vec{dl}\times\vec{B}. \qquad (2)$$

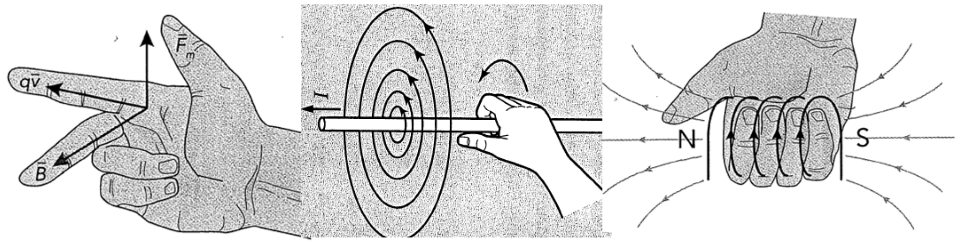
The law of magnetic force, which relates the vectors of force (*F*), velocity (*v*) or the current element (*dl*) and the magnetic field (*B*).

These interpretations of the Biot-Savart and the magnetic force laws are often reduced to the so-called Right-Hand Rules (RHRs), which are applied in a highly symmetrical and simple situation shown in Figs. 1a, 1b and 1c. Due to the complexity and high degree of abstraction involved in the exact explanation of magnetic field and magnetic force, it is tempting to learn the outcome of the simple cases – the Right-Hand Rules. If used logically and correctly, it certainly works effectively in solving some problems.

As a result of reducing the demand for vector calculus at upper secondary school level, however, the relations referred to are typically expressed in scalar form, and the directions are required to be memorized by using the Right-Hand Rules. The Right-Hand Rules are context dependent and they are not named after any specific situation. Hence, the limitations of applying such rules are frequently accompanied by no explanation, and it can be tempting for the rules to be used too generally or too narrowly. The Right-Hand Rules are in fact used to show the general orientation of the field or the force, and the essential character of both is that they are vectors that are represented by the pointing or curled fingers.

The key at university level to understanding such magnetic interactions is linked with an understanding of how the 3-dimensional vector fields are formed from their sources and of the basis on which they cause force interactions. Furthermore, the basis of any understanding of the vector character of the field and force and their cross-production originates from the relevant relations and is hence essential for a profound understanding of the basic magnetic concepts [10]. This can be regarded as a preliminary step towards an understanding of the abstract model represented by Maxwell's equations. Based on the discussion of the difficulties that have been recognized in understanding magnetic field and force, our research question was formulated as: *How do students comprehend the magnetic field caused by the distribution of a current and a magnetic force acting on a moving charge and a current-carrying wire?*

It is important for physics educators to know the kind of pre-conceptions that students possess of the issues to be learned. Effective teaching can only happen when students' earlier knowledge is taken into account in the design and implementation of teaching [11, 12]. In our own case, the students' conceptions play an even more important role than usual because the content of the teaching is known to be highly demanding for students, and a teacher will have to play an important role in helping the students to grasp the concepts and phenomena. If a teacher aims at teaching for a deep understanding, s/he will certainly be aware of her/his students' thinking and understanding of the particular issues that can be considered essential basic knowledge [13]. In our present study we have used the results of students' understanding as a corner-stone of the Educational Reconstruction of a teaching unit in magnetostatics, as reported in the second part of this study.



1a) 1b) 1c)

FIGURES: 1a, 1b and 1c. Upper secondary school textbook illustrations of the Right-Hand Rules for a) Magnetic force, b) The magnetic field of a DC wire, and c) For a solenoid [8, 9].

II. METHODS

This study was implemented in 2009 at the University of Kuopio, which now forms a part of the University of Eastern Finland. Our subject group consisted of 38 first-year university students taking a basic course in electromagnetics. Most of the students were majoring in physics.

The students were given a written test which dealt with magnetic fields and forces, as shown in Fig. 2. The questions resembled the referring questions used in the CSEM and BEMA base-line performance tests [14, 15]. In order to obtain a better insight into the students' understanding, seven of them were asked to participate in a semi-structured interview based on the test questions. The students interviewed were also required to explain their answers [16, 17].

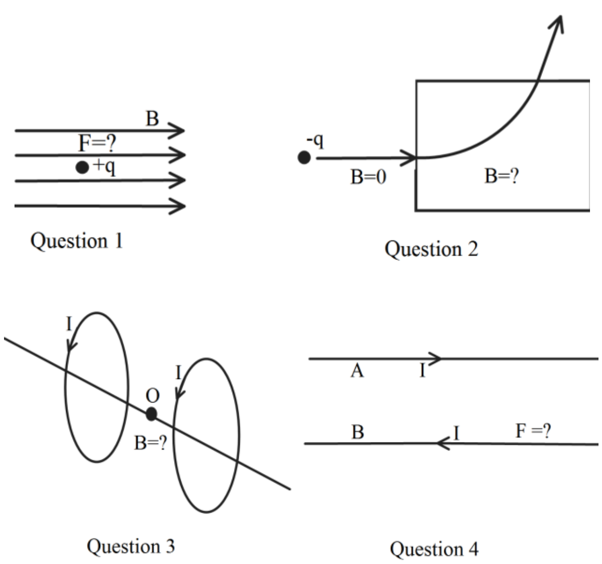


FIGURE 2. The test questions concerning the direction of magnetic field and force. The possible directions for the answers were given as "right", "left", "up", "down", "into page", "out of page", "zero" or "none of these".

Question 1: A positive charge +q is at rest in a uniform magnetic field. What is the direction of the initial force on the charge?
Question 2: At a constant velocity a negative charge is entering the vicinity of a uniform magnetic field. Based on the trajectory shown in the diagram, show the direction of the field.
Question 3: Show the direction of the magnetic field at the mid-point of two rings of current.
Question 4: Two parallel DC wires, A and B, carry a current in opposite directions. Show the direction of the magnetic force that wire A exerts on wire B.

All of the test questions represented simple cases where using the Right-Hand Rules would provide correct answers. In the semi-structured interviews the students were subsequently asked to explain their reasoning in the answers they had provided in the written test. In addition, particular interest was paid to the ways in which the students understood and applied the rules in the cases of field and force. The interviews were videotaped.

The students' answers in the written test were categorized on the basis of both Guisasola's classification [6] and the responses made by the students in interview. Questions 1 and 2 formed a single subset dealing with the law of magnetic force and Questions 3 and 4 a subset dealing with Biot-Savart (Question 3) and Biot-Savart/magnetic force law (Question 4). The question subsets differed in one significant respect: Questions 1 and 2 were based on the Right-Hand Rule illustrated in Fig. 1a). This particular rule is used as a problem-solving tool to determine force, field and velocity [trajectory] in the case of a moving charge in the magnetic field. The rule is useful in a variety of cases. On the other hand, the rules concerning the field of a current distribution, as shown in Figs. 1b) and 1c), are highly case-specific and with limited and idealized applications: they simply show the final result of the integration of the Biot-Savart law in special cases. For this reason we have combined questions 1 and 2 to gain more complex information about the of students' reasoning concerning the various fields and forces, while questions 3 and 4 are treated separately so that we could to find out how students memorize the referring rules in particular situations.

III. RESULTS

The results are presented in two sections. First, the general results related to the set of questions in the written test are presented, and then the results of the test are discussed in detail, with examples taken from semi-structured interviews conducted with selected students.

A. General test results

The students' initial understanding of magnetic field and force was measured by means of a written test. Table I shows the total scores achieved by the whole subject group and the individual answers provided by the interviewed students.

TABLE I. Students' answers and scores related to the written test questions (N=38). The interviewed students' answers are shown in detail.

Total N = 38	Question 1	Question 2	Question 3	Question 4
Correct N	7	9	17	7
Interviewed students				
Student 1	right	down	left	out of p.
Student 2	left	up	left	zero
Student 3	up	out of p.	left	-
Student 4	right	up	down	left
Student 5	zero	into p.	left	out of p.
Student 6	zero	left	left	zero
Student 7	into p.	into p.	left	down

The general results show that the question concerning the field in the axis of a current loop (Question 3) had apparently been well memorized. However, all of the remaining cases where magnetic field (Biot-Savart law) and magnetic force (Lorenz force law) should have been used turned out to be difficult and the answers were split between several alternatives.

B. Detailed results in the written test and interviews

In this section, the students' answers are discussed in more detail with respect to Questions 1 and 2 (the magnetic force on a charge), Question 3 (magnetic field due to a current), and Question 4 (magnetic force between two current-carrying wires). Instead of analyzing the questions separately, we looked at those that shared the same physical background in order to detect potential coherence in students' thinking. We also considered it likely that by looking at the questions in combination it would be possible to perceive students' understanding in a more holistic manner.

Our analysis of the written test was based on the most important findings of previous studies such as the analogy to the E-field [2, 6, 1]. In addition, an initial analysis revealed a number of new categories concerning mistakes in the use of the Right-Hand Rule. The categories formed were verified in course of the interviews held with selected students.

C. Magnetic force on a charge

The reasoning underlying correct answers to Questions 1 and 2 is based on the law of magnetic force and hence the two can be combined. Table II shows our categorization of students' answers to these Questions. The variations in the options found in the answers can be placed in four classes.

TABLE II. Categorization of students' answers regarding their use of coherent ideas of the Right-Hand Rules.

Category	Number of answers to the combined test Questions 1 and 2 [N=38]
The Right-Hand Rule used correctly	3
Incorrect use of the Right-Hand Rule	7
Incorrect analogy to the E-field and force	8
No coherent ideas regarding the B–field and force found in the given situations	20

As Table II shows, the group of students in the final category (20 of 38) was large. This was partly due to the difficult necessity to demonstrate coherent logical thinking in both questions, and also partly due to the categorization. However, the number of answers in the final category indicates that concepts of magnetic force and field are very vague. If no exception had been made by permitting, in one case, a sign error, there would have been no totally correct combined answer.

The Right-Hand Rule (RHR) used correctly. Here we have accepted "into the page" as the answer to Question 2, which means that the sign of the particle has been merely guessed at in the RHR. Student 5 was the only interviewed student in this category. He revealed the reasoning behind his answer by using the fingers on his right hand and the referring rule, as in Fig. 1a). However, he also made a mistake in the interpretation of the sign in Question 2.

Incorrect use of Right-Hand Rule (RHR). This category consists of answers that demonstrate the orthogonality between the field and force, where the force is perpendicular to the field, giving the impression of use of the RHR, although in different variations of the RHRs velocity, field and force are not dealt with correctly. *A typical mistake was to apply the rule by discarding the fact that the charge is at rest*. The link between the "direction of the finger", the vectors and the cross-product, is thus very vague, *i.e.* the order of the cross-product remains unknown. In this category we have decided that the answers to this pair were wrong if either of the two answers was wrong, even if the answers included the idea of orthogonality.

In interview, student 7 also used the Right-Hand Rule by showing the fingers and explaining the meaning of the rule. She gave an acceptable answer to Question 2, although she made a mistake in interpreting the sign. However, she had also made a mistake in answering Question 1. She pointed her middle finger to show the direction of the magnetic field and consequently her thumb was pointing in the direction of the force. The correct choice would have had the thumb pointing into the page. In addition, she did not interpret the zero value of the velocity.

Incorrect analogy to E-field and force. Magnetic field and magnetic force are misunderstood as an analogue of an electric field, *i.e.* field and force are regarded as parallel and the field thus gives rise to an acceleration of the particle in the direction of the lines of field. This category has been formed from paired answers in which the field and force are stated to be parallel. The reasoning behind the answer can be described as an incorrect analogue between the electric and magnetic fields and force. The magnetic interaction is regarded as being exactly the same as in case of an electrical interaction.

An example found in the answer provided by student 1: "Force is directed in the B–field and it (the particle) accelerates in the same direction. ... The situation would not differ if there were an E–field instead of the B–field. ... If there were a change in the magnitude of the charge, speed, or the field, the magnitude of the force would change, but not the direction".

Student 2 also seems to have made an additional mistake in defining the concept of force: "…after some time the force would set up a steady velocity".

No coherent ideas concerning the B–field and force in the given situations. The directions of the force and field are arbitrary, with no linkage between them. The requirement to demonstrate correct or coherent thinking in both questions is the reason for the large number in this particular class.

1. Magnetic field resulting from a loop of current.

Question 3 is an example of the Biot-Savart law. A field resulting from current element can be computed in any arbitrary location by integrating the infinitesimal elements through the current distribution. In the particular cases of an infinite line (field everywhere) and a loop of current (field in the axis), the resulting direction of a field can be deduced using the Biot-Savart law and expressed by using the referring Right-Hand Rule, as shown in Figs. 1b) and 1c).

The students were not expected to provide a formal answer to Question 3. This question measures their general ability to use this special case of the Right-Hand Rule correctly. In addition, the two fields resulting from the loops should be added together as vectors. As a result of the absence of any formal physical explanation in the students' background studies, we categorized the test responses as either correct or incorrect, and then looked more closely at the students' reasoning in the interview (see Table I). The correct answer to Question 3 is thus the result of proper use of the Right-Hand Rule. There is a possibility of interpreting the picture in such a way that the direction of the current is opposite, in which case the rule of thumb would indicate the opposite direction as an answer. Four students selected this option. The following provides examples of the other interviewed student's ideas related to Question 3.

Student 1: "The Right-Hand Rule gives the field, and the force is directed towards the field".

Student 7: "Curled fingers along the current: the thumb points to the force".

Student 3: "The Right-Hand Rule states that the thumb is directed towards the current and the curled fingers give the field".

The reasoning produced by students 1 and 3 included using the Right-Hand Rule in the following way: the right thumb points in the direction of the current and the curled fingers show the direction of the field. However, the students changed their answer frequently in the course of the interview, because they could not decide on the actual direction of the field based on this rule in the case of current loops. In addition, student 3 said that the rule applies in the near proximity of the current. He was not sure about the behaviour in other locations. Students 1 and 7 represent the group who thought that the magnetic force was in the same direction as the field.

D. Magnetic force between two current-carrying wires

Question 4 is an example of the use of both the Biot-Savart law and the law of magnetic force. In this case, the correct reasoning could be expected to be made up of two different Right-Hand Rules applied in sequence or from memorization of the special case of parallel infinite DC wires.

With respect to question 4, the force on the wire B is repulsive. There were a lot of answers (13 out of 38) that referred to an attractive force, which may indicate a mistake in memorizing the forces in this special case. Student 4 was the only student with a specious correct answer in the interview, and analysis of her interview revealed that the researcher should be cautious with further assumptions:

Student 4: "The magnetic field points in the same direction as the current, which gives the answer 'down'".

In the case of question 4 there were 10 answers that said that the force on wire B was in the same direction as the field set up by current in wire A. It was found that students also tended to confuse field and force in their earlier studies [2]. Student 1 was the only one with a coherent [mis]conception: s/he answered questions 1, 2 and 4 incorrectly, but also correctly in a logical sense, so we cannot state categorically that there can also be students who follow their own incorrect logic in particular situations.

Selected examples of incorrect answers from the interviews related to Question 4:

Student 7: "The forefinger points in the direction taken by current A and the middle finger is directed down to the magnet, so the thumb is directed down, which gives the force as downwards".

The student could not clarify what was the "magnet" nor why the middle finger was directed into the page. She said that "*this is what the right hand gives*". Her correct answer is thus simply guesswork.

Student 2: "I do not recognize the presence of magnetic interaction".

Student 4: "The B-field is directed either towards or away from the current". Misusing her own rule, she continued: "Current 2 experiences the force along the field, which therefore gives the answer 'to the left'".

These students somehow connect the Right-Hand Rule with the situations described. This includes interpretation of the fingers of the right hand that represent the direction of the particle or current, the direction of the field, and the direction of the force. However, the rule either remains unused or it has been memorized incorrectly. The rules are not based on any physically correct ideas or explanations. Overall, there was only one student who provided correct answers to the essential Right-Hand Rule cases numbered 2, 3 and 4, but even she made a mistake in answering Question 1.

IV. CONCLUSIONS

In the present study we have examined first-year university students' initial knowledge of magnetic field and force. From our experience of the students' previous education, the practical knowledge underlying their correct conceptions of magnetic field and force have undergone reduction from the Biot-Savart law and the law of magnetic force into certain Right-Hand Rules. Nevertheless, the students who were interviewed and who had heard about the Right-Hand Rules either did not use them or used them wrongly or inconsistently.

To be able to follow the traditional course of instruction in electromagnetism at university level, students should have a quite consistent grasp of the concepts of magnetic field and force. In fact, questions 1 and 2 measure the baseline of these concepts. There were, however, only three students who were able to provide acceptable answers to both of these Questions. Even when using evidence based on the Biot-Savart law or the law of magnetic force correctly but without proper comprehension, students who applied the RHR should be regarded only cautiously as "Amperian" thinkers as they are according to Guisasola's classification [6]. In our opinion, to call a student an Amperian thinker s/he 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 a lack of referring instruction at the secondary school level. The majority of students still have unwanted concepts or flaws in their thinking that prove to be obstacles when they attempt to follow the traditional university-level courses.

Nevertheless, the students who came into the second category of incorrect use of the Right-Hand Rule demonstrated fruitful thinking in trying to apply the Right-Hand Rule in the given situations. One example of this was the result in the case of question 1, where 16 students out of 38 thought that there was a magnetic force perpendicular to the field acting on a particle at rest. The students who mistakenly drew analogies with electric field and force were also unable to use the concept consistently. This kind of thinking is relevant when these students need to learn how to explain their reasoning by using the force and field relations with the correct vector calculus. The Right-Hand Rules have been derived and reduced from the cross products and thus the students' use of the rules – even with minor flaws – provides a starting point for reconstructing the teaching.

The main idea when designing the teaching with the students who set up the false analogy with the E-field is to help them to recognize the difference in nature between the electric and the magnetic interactions, especially the requirement of taking into account the velocity of the particle, and also the current as an essential element within the referring connections between field and force.

Regarding questions 1 and 2, the last and largest category that reveals a poor grasp of concepts and a poor coherence in the comprehension of magnetic field and force concepts is the one that establishes the baseline when designing the course of instruction. Our findings suggest that by interconnecting the different representations of magnetic field and force, *i.e.* the graphical representations of the vector fields, the mathematical equations and the referring explanations and the rules of thumb, it is possible to create a successful route to learning that takes into account the initial concepts held by the students. An example of the way in which the graphical and mathematical connection can be enhanced in a related field is given in Chabay's and Sherwood's textbook on electricity and magnetism [10].

With respect to Question 3 concerning the field around a current loop, it appears that students seem to memorize the referring Right-Hand Rule reasonably well. Previous studies also show, however, that the concept of field is strongly related to its representation – the curled fingers, in this case – and it is common that field strength and direction appear to be difficult to visualize in more distant locations or in a non-symmetrical situation [2]. Nevertheless, in this particular case students' success has been promising since the use of the Right-Hand Rule provides a good context for learning the interpretation connected with the relevant vector.

Finally, students' answers to Question 4 indicate that successfully and coherently applying the two different rules in sequence seems to constitute a challenge. Students would rather use a memorized conclusion for the specific case of two parallel current-carrying wires. Since it would be an interesting approach to introduce such a situation into a pre-test, it is important during the instruction to demonstrate the correct sequential treatment of field and force relations in non-symmetrical cases in which current carriers exert forces on each other.

In sum, the number of students returning incorrect answers to questions 1 and 2 shows that it is easier to demonstrate what is not understood than what is understood. A majority of the students in our present study seemed not to possess a logical context for their explanations. Hence, it is our conclusion that their descriptions of magnetic field and force have only a very weak coherence and are based on loosely connected rules of thumb, electric analogues, and various false explanations. In other words, students fill the vacuum, the need to provide an explanation, with something that seems to satisfy them to some extent. Nevertheless, they were rather reluctant to defend their explanations, for example, in interview. Thus, the instruction at university level should be based merely on reviewing the relations in their vector form and reconnecting the referring rules to a more comprehensible context.

On closer inspection, it becomes apparent that our results agree with Furio's and Guisasola's: students do confuse the concepts of field and force by thinking of them as being in parallel [2] and as possessing the electrical disanalogues categorized in previous studies [6, 1]. It would, then, appear even more necessary for Maxwell's equations to be taught and learnt at university level, given the flaws that there are in the preceding steps involving the Biot-Savart law and the law of magnetic force.

Our results reveal that the Right-Hand Rules learned in preceding studies at upper secondary high school do not offer a sufficient theoretical background for understanding the rules properly. This is not surprising since the cross product does not currently exist as a component in the obligatory courses in mathematics, nor are cross products introduced in the physics courses taught at Finnish upper secondary schools. In addition, no emphasis is placed on the vector characters of the fields. The Right-Hand Rules give relatively good results in the solving of problems that are highly symmetrical and simple, but the simple rules seem to be like memorized cookery book instructions, with only a very limited power in problem-solving or in explaining magnetic phenomena [1, 3]. If used correctly, however, the rules are helpful in providing suggestive directions for force and field, but, alone, they are insufficiently powerful to be able to replace the original vectors. The rules are also difficult to remember, since the relevant scalar relations are not strongly linked.

The results of this study also suggest that the teaching dealing with electromagnetics should be reviewed. Based on our results, the instruction at university level would need to start by reviewing the underlying principles of magnetostatics from the level that is taught formally at the upper secondary school. In particular, the basic features of magnetic force and field should be reconsidered. We found no coherent competitive or alternative misconceptions that might offer any obstacle to the proper learning of the desired model of magnetostatics in general. The disanalogues to electric field and force seem to be vague and incoherent, simply fulfilling the students' need to have some kind of explanation rather than nothing at all. The real challenge is to be able to provide a more powerful explanation for the Right-Hand Rules by referring to the vectors.

In our subsequent study, we will use students' conceptions of magnetic field and force to design a teaching sequence. In the following paper, which will deal with the teaching sequence, we will discuss the issues that are essential from a theoretical point of view and that will be challenging for students themselves. The main implication of this study for the teaching sequence will be to strengthen vector thinking and the physical interpretation of the Biot-Savart law and the law of magnetic force. Clearly, the main obstacle to students' learning about magnetic field and force is their vague grasp of the concept of field and especially of the relevant vector relations. Magnetic field and force cannot be understood correctly without three-dimensional vectors. Thus, comprehension of magnetic force and field will require a new approach where students are introduced to field and force relations through graphical, mathematical representation, their interconnections and where the rules of thumb are connected together as a meaningful tool of thinking. In adopting this approach, we believe that an understanding of further topics in electromagnetic field theory, including those that are strongly vector field dependent, can indeed be achieved. But without an awareness and understanding of students' misconceptions of the basics of magnetism and without constructing an effective comprehension of vector thinking, it attempting to teach such topics as Ampere's law would remain frustrated.

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