Developing instruction in magnetostatics at undergraduate level
Part 2 Multi-step tasks as an instructional tool resulted from Educational Reconstruction

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Abstract

In this study the model of Educational Reconstruction was used to develop a teaching sequence in university magnetostatics to help students to learn the concepts of magnetic field and force. A developed teaching sequence with novel multi-step tasks was implemented and student learning was monitored. The results indicate that students' learning results were better 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 in support of their thinking and in problem-solving in magnetostatics. It seems that Educational Reconstruction is a functional method for making use of recognized learning difficulties, the physical content and the aims of the instruction in developing effective teaching in physics. This article is the second part of a study whose empirical background is reported in Part 1.

Keywords: Undergraduate, electromagnetics, magnetic field concept.

Resumen

En este estudio el modelo de la Reconstrucción Educativa se utilizó para desarrollar una secuencia de enseñanza en la universidad magnetostática para ayudar a los estudiantes a aprender los conceptos de campo magnético y fuerza. Una secuencia de enseñanza se desarrolló con nuevas tareas multi-pasos implementadas y aprendidas por los estudiantes que son monitoreados. Los resultados indican que la resultante del aprendizaje de los alumnos es mejor después de la implementación de la secuencia de enseñanza y algunos errores típicos podrían ser evitados. Además, los estudiantes aprendieron a utilizar las relaciones vector como un método de gran alcance en apoyo de su pensamiento y en la resolución de problemas en magnetostática. Parece que la Reconstrucción Educativa es un método funcional para hacer uso de las reconocidas dificultades de aprendizaje, el contenido físico y los objetivos de la instrucción en el desarrollo de la enseñanza efectiva de la física. Este artículo es la segunda parte de un estudio empírico, cuyo fondo se presentan en la Parte 1.

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

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I. INTRODUCTION

Usually, an electromagnetic field theory course in first-year university studies involves Maxwell's equations in their integral forms. Indeed, treatment of magnetostatics is relatively challenging for students due to the expansion to the three-dimensional geometry and the use of vectors along with integrals [1]. Learning Ampere's law also requires an understanding of the relationship between vector fields, the path integral, and its physical interpretation with the enclosed current distribution. Hence, before the start of Maxwell's formulas in the teaching of magnetostatics, students' comprehension of these building elements needs to be ensured. In consequence, the concepts of magnetic field and force as presented by the Biot-Savart law and magnetic force law are essential for an understanding of the basics of magnetostatics. Nevertheless, this is not a straightforward process for students, and several difficulties in learning may be encountered.

The possible reasons for learning difficulties in relation to magnetostatics include confusion between magnetic field and magnetic force [2]. Typically, magnetic field is misinterpreted as analogous to electric field or magnetic behavior considered as an inherent property of matter [2] [3]. Due to misanalogy with the concepts concerned with electric field, the magnetic field vector becomes difficult in a physical context. Vectors in electromagnetics are understood better in the case of forces than of field, and students persisted in maintaining a Newtonian model of “action at a distance” [4, 5, 6]. Mathematics is understood as a method of problem-solving but not as a constructive thinking tool with a physical interpretation [4]. In the case of magnetic field and force, the relations include physical interpretation of the cross-product. For some of the first-year university students on our course, this is evidently a new mathematical tool in the field of magnetostatics. Nevertheless, the cross-products, and hence both the referring three-dimensional topology of the field and also the interpretation of the force, prove to be the essential nodal points in students’ understanding of the concepts of magnetic vector fields and the vector character of the force.

A number of reports have already been published concerned with instructional perspectives related to magnetostatics at university level. One approach to the topic devised by Marr was based on a four-step modification of homework exercises designed to improve students’ basic skills in problem-solving [7]. The first component dealt with units, while the second component was a set of routine mathematical problems related to the mathematical operations to be employed in the topic. The third component was a set of multiple-step, conceptual problems, and the fourth was a set of simple one- or two-step physics problems. In a study made by Guisasola an intervention was developed to help instructors to identify students‘ Newtonian (F=ma) and Aristotelian (F=mv) mental models of magnetism as a guideline for instruction [8, 7]. According to Chabay and Sherwood, if the concepts of the field and force are introduced too closely together, they will become laborious for students and difficult to assimilate as a result of the equivocal mental rotations. Thus, for example, topics related to magnetic field are likely to be followed by topics on electric current before magnetic force has itself been introduced [9].

There are, however, only a few published research articles concerned with the learning and teaching of the basics of magnetostatics at university level. In addition, no reports have yet been published that are concerned with functional instructional solutions for fulfilling the gap between upper secondary school physics and university physics in magnetostatics. Our aim is, therefore, to fill this gap. In order to achieve this aim, we posed the following research question: “How can we design and evaluate an effective teaching sequence in magnetostatics that will take into account the structure of physics, the student’s conceptions, and the teacher’s views?”

To answer this question a new teaching sequence was designed in support of teaching the topics of magnetic field and force, and in this developmental work the model of Educational Reconstruction was used as the theoretical frame [10]. The aims of our previously reported instructional interventions were to improve students’ adoption of the desired scientific model of magnetism and to promote their problem-solving skills [3, 7]. In the present study we took into account the aims of the instruction, the students’ initial knowledge and also 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 law and magnetic force law.

II. THE MODEL OF EDUCATIONAL RECONSTRUCTION

The model of Educational Reconstruction is a method for designing instructional units [11, 12]. Typical of the educational reconstruction that it promotes is that it emphasizes the close connection that exists between the theoretical and practical aspects of designing teaching sequences in physics. The educational reconstruction itself brings science content-related issues and educational issues into balance when teaching and learning sequences are being designed [11, 12].

The method used in Educational Reconstruction consists of three inter-connected components: 1) Analysis of content structure, 2) Research on teaching and learning, and 3) Development and evaluation of instruction (see Fig. 1). The components interact closely with each other and are not arranged in any particular order. Instead, the use of the model can be considered a cyclic process [11]. The first component in this study is, therefore, a reconstructed theory of magnetostatics that includes the student’s preconceptions in addition to the design and evaluation of the teaching sequence per se. Secondly, the empirical research consists of students’ preconceptions of magnetostatics, as reported in Part 1 of this study and also in earlier studies [3, 2]. It also contains an analysis of teaching materials and of teachers’ views and conceptions of the teaching and learning processes. Thirdly, the development and evaluation of the teaching sequence will be carried out based on the information obtained partly from the students’ learning results and partly from a detailed analysis of how the goals of the teaching have been achieved.

Using the model provided by Educational Reconstruction as a basis for designed instruction is not to re-invent physics or to reduce the depth of theoretical treatment. Rather, this method can be described as a tool for reshaping the instruction and making it more accessible to students [11]. The results of the educational reconstruction process can be seen as a set of practical guidelines for teaching that takes into account the aims of the teaching by considering both the teachers’ view and the students’ conceptions and potential learning problems. At this stage, therefore, it would appear useful to discuss in detail the components of Educational Reconstruction as they appear in this study.

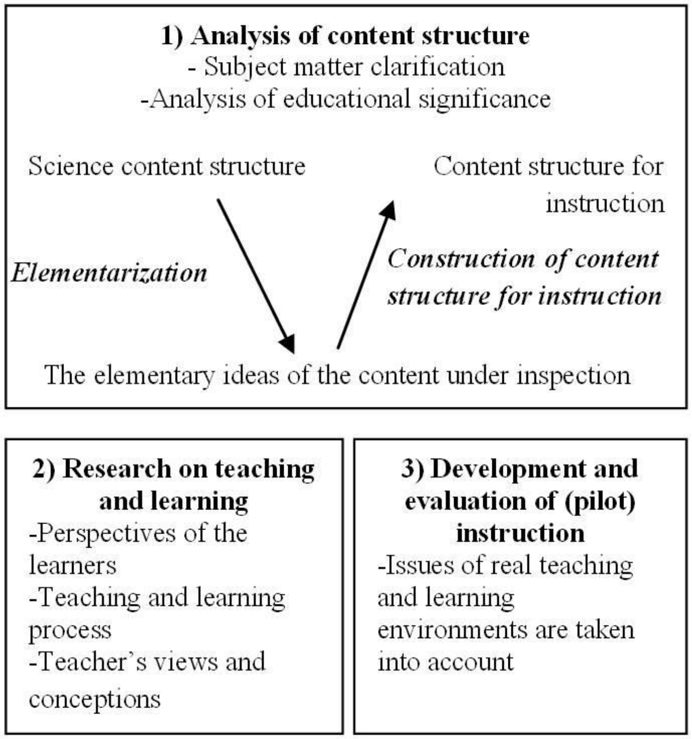

FIGURE 1. The Model of Educational Reconstruction [11].

A. Analysis of content structure

The basis of magnetostatics rests on the concepts of field and force as represented in the Biot-Savart law and the law of magnetic force [13]. In addition, the non-conservative character of 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, since, when linked correctly together, these will result in a correct use of the referring Right-Hand Rules. Unlike in electrostatics, the relationship involved in the field cannot be derived from the force. This is due to a missing analogical force law comparable to Coulomb's force law since there are no magnetic monopoles of a magnitude equivalent to the electric charge. In addition, the magnetic force law is expressed in terms of magnetic field. Thus, introducing the field before the force in the teaching is logically valid. The elementary idea of reconstructing the teaching of the Biot-Savart law and magnetic force law is to provide students with vector-formed relations that can be used as active tools in thinking, explaining and problem-solving.

B. The elementary ideas of the content under inspection

Previous articles have shown that students have the following major difficulties in learning about magnetostatics: Difficulties in distinguishing between force and field [2], using an incorrect analogy to electricity [3], and using of the Right-Hand Rules conjecturally and hence with no physical basis (our result, as presented in Part 1). In addition, the largest group in our previous study seemed to possess no logical foundation for their explanations. It was our conclusion that students in fact possess no coherent basis for explaining magnetic fields and forces. Some students are nevertheless familiar with the Right-Hand Rule. The Right Hand Rule, if explained correctly, works in accordance with a scientific concept. Hence, we chose to review the relationship existing between the Biot-Savart and magnetic force laws by advocating correct treatment and a physical interpretation of the vectors involved. A detailed description of the students' learning results has been presented in Part 1 of the present article.

C. Content structure for instruction

The general result of the reconstructed theory based on the three components of Educational Reconstruction introduces the four steps in learning magnetostatics and their interdependence in an increasing hierarchical order. The steps are following: Step 1. Source of magnetic field (Biot-Savart law); Step 2. Magnetic field topology for moving charge and current distributions; Step 3. Magnetic force (Lorenz-force); and Step 4. Graphic representation of magnetic force. The practical implementation of the reconstructed instruction consists of a set of 20 multi-step tasks and problems, which are presented displayed in detail in Appendix A. In earlier studies concerning the learning of electromagnetism [7] and of quantum physics [14], introducing multi-step problems and tasks in the course of lectures has been shown to be effective. Instruction consisted of the lectures, homework, and tasks carried out in small groups during the lectures.

D. Development of instruction – multi-step tasks in teaching

Steps 1 and 2 consisted of tasks 1-12, which were combined with the teaching when dealing with magnetic field, while steps 3 and 4, in turn, consisting of tasks 13-20, were combined when dealing with magnetic force. The tasks shown in Appendix A were carried out in small groups during lectures. The students were invited to discuss their answers in groups with their peers. At the end of each task – each of which lasted a few minutes – the answers produced by each of the groups were pooled, and it was found that in every case the correct answer had been found by the students in one or more of the groups.

Steps 1 and 2 (See task group S12 in Appendix A). In our previous paper (Part 1) we discovered that students had found it difficult to distinguish between electric field and magnetic field. In addition, the correct method of applying the Right-Hand Rule was found difficult due to the absence of adequate application and interconnection with equations related to the referring vector. 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. This is illustrated in Task 1, where the field is observed in non-orthogonal locations. This aspect emphasizes the fact that the Right-Hand Rule is not solely applicable in its own right in every situation as is the case in Tasks 5 and 6. Another important aspect is for students to learn how to draw and use the notation of the vector presentation graphically [14]. Learning how to interpret and draw the vector becomes important since the mathematical formula of the Biot-Savart law does not indicate where the resulting vector of the cross product is located. Task 2 provides a good example of how the field vectors are drawn. Here, the resulting magnetic field vector is interpreted from the point of observation. Hence, it is necessary to show students the graphical representation at the same time as its mathematical equivalent. Restricting instruction to the Right-Hand Rule – especially by taking it too literally – would restrict students' understanding of the three-dimensional geometry of the magnetic field. The nature of the vector and, respectively, the superposition of the fields are considered in Tasks 9-12, which involve multiple sources. Another practical approach involves displaying the fields of a solenoid and a bar magnet and initializing the idea of bound surface current distribution as the underlying reason for the magnetic fields of permanent magnets and magnetic materials, as demonstrated in Tasks 7 and 8.

Steps 3 and 4 (see Task group S34 in Appendix A). A significant finding concerning magnetic force presented in Part 1 of this article was that students tend 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. The tasks presented here as examples are based on problems concerning the magnetic force on a moving charge or on an infinite direct current wire. The law of magnetic force is applied in both cases. Again the tasks promote understanding of the resulting force as the result of the vector cross product. Tasks 13-16 illustrates a situation in which the force is acting on the charges and wires. In addition, the tasks include examples where students are obliged to abandon the Right-Hand Rule as their primary problem-solving tool. The cases of non-orthogonality in Tasks 13 and 15 on charge q_3 are particularly important for demonstrating the power of vector thinking. In cases involving non-symmetrical situations or where the cross product vectors are not perpendicular also demonstrate how the Right-Hand Rule can become rather a suggestive way of predicting the direction of the force. The exact force vector is needed to solve the value of the force. At the end of the task list, Tasks 18-20 include the use of both field and force relations. These Tasks emphasize both the sequence and the route involved in solving the problem: the field first, and then the force.

The main idea underlying the development of the instruction was a desire to emphasize the essential role played by 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 will understand both the origin of the rules and also the area in which the rules can be applied.

III. EVALUATION OF EDUCATIONAL RECONSTRUCTION IN MAGNETOSTATICS

A. Methods

To gain an understanding of how the students achieved their learning goals, during the course they were tested using a set of test questions concerned with magnetostatics. The same written test was given not only at the end of initial phase of the course but also following the teaching sequence on magnetostatics. In outline, the test questions dealt with the following:

Question 1: (Force) The magnetic force on a charge at rest in a magnetic field.

Question 2: (Force) Prediction of the direction of a magnetic field based on the trajectory of the moving charge.

Question 3: (Field) The direction of the magnetic field midway between two rings of current.

Question 4: (Field Force) The magnetic force present in the case of two parallel DC wires.

The test questions are described in detail in Part 1 of this article. In order to ASSESS students' knowledge on the Biot-Savart law and magnetic force law in asymmetrical situations, one of the problems was designed as a part of the final examination (Fig. 2). Asymmetrical cases cause students to use the Right-Hand Rule as a supportive tool of thinking, while the use of vector-formed relations would provide the correct answer.

In the figure below there are three parallel DC wires carrying, respectively, currents I_1 =1A, I_2=2A and I_3=3A into the page, *i.e.*, towards the negative z-axis. The conductor I_1 passes through the xy –plane at the point (1.0)[m], current I_2 through (2.0)[m], and current I_3 through (0.1)[m].

a) Derive the magnetic field (**B**[T]) resulting from the currents I_1 and I_2 in the location (0.1)[m].(5p)

b) Derive the total magnetic force of unit length in current I_3.(5p)

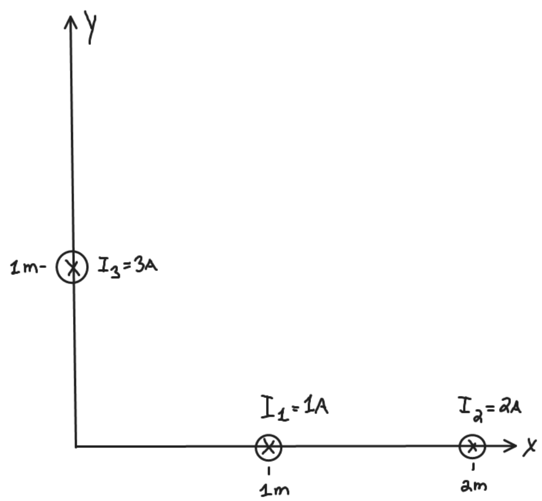

FIGURE 2. The problem involving magnetic field and magnetic force in the case of direct current carrying wires in the final examination.

Figure 2 shows a system of wires arranged in a way lacking symmetry and thus the use of the vector relationship would be required to produce a correct answer concerning the field. In the case of the force, the resulting field and the direction of the current element were perpendicular. In this particular case, there was therefore the possibility either of using the result B–field from Part a) or of calculating the forces separately as a result of currents I_1 and I_2.

B. Results of the written test and final exam problem

Students' pre- and post-scores for the written test questions 1-4 are presented in Table I.

TABLE I. Students pre- and post-scores in the written test. The domain of questions related to magnetic field and force relations are shown on a gray field.

	Question1 Force on a charge at rest	Question2 B-Field causing a moving charge to move on a curved path	Question3 B-field resulting from two rings of current	Question4 Magnetic force on a parallel DC wire
Pre-test correct Total N = 38	7	9	17	7
Post-test correct Total N =21	16	17	11	12

Table I shows the extent to which students' performance in questions 1, 2 and 4, which were concerned with the magnetic field and force in the domain of direct use of the Biot-Savart law and magnetic force law as a background to the Right-Hand Rule had undergone improvement. The results for question 3 concerning the field of rings of current were approximately the same.

If students' answers to Questions 1 and 2 are reorganized in the way suggested in Part 1 of this article, the main finding is of a coherence in using the ideas of the concepts of magnetic field and force correctly in these simple cases (see Table II).

TABLE II. Students' pre- and post-test answers to questions 1 and 2.

	Question 1 and Question 2: Direction of the force and direction of the B-field (number of answers) Pre-test (N = 38) Post-test (N = 21)	
Correct use of the Right-Hand Rule	3	15
Incorrect use of the Right-Hand Rule	7	1
Incorrect analogy with E-field and force	8	0
No coherent ideas concerning what the B–field and force are in the given situations	20	5

As can be seen in Table II, there were only 3 correct answer combinations in the pre-test. In the post-test, however, the number of correct combinations was 15, which suggests that the magnetic force equation had been understood and used correctly, including the significance of velocity and of the sign of the moving charge. It should also be noticed that no students were now attempting to draw an incorrect analogy with the parallel electrical concepts.

A total of 34 students participated in the final exam. Their answers (Fig. 2) can be placed in four categories (Table IV).

TABLE III. Classification of students' answers to the final examination problem.

Category	Number of students
Correct	18
Incorrect, but with minor flaws, *e.g.*, mistakes in calculus	7
Incorrect, with no vector thinking	6
Incorrect blank in a) and scalar thinking in b)	3

Correct answers include the use of the correct vector thinking. The field resulting from the infinite DC wire, which was derived from the Biot-Savart law during the lectures, can be stated as $\vec{B} = \frac{\mu_0 I}{2\pi r}\hat{a}_r$, where $\hat{a}_r$ is a unit vector pointing in the direction of $\widehat{dl} \times \hat{r}$. The unit vector $\widehat{dl}$ is the vector of the wire segment pointing in the direction of the current while $\hat{r}$ is a unit vector pointing from the source to the point of observation, respectively. In order to provide correct answer to question a), students needed to compute the field as vectors for both currents I_1 and I_2 and to use the superposition principle in adding up the two field vectors. Due to the non-symmetry and the need to provide an exact value for the resulting field, the use of the Right-Hand Rule would have been insufficient in this particular case. The correct method of computing the force is quite straightforward, requiring use of the magnetic force law for an infinite current carrying wire in a constant magnetic field. In this particular case, the field and the current segment(s) are perpendicular and thus lead to a relationship that gives the force on the unit length: $\frac{F}{l}$ =IB. The direction of the force results from the cross product $\overrightarrow{dF} = I\widehat{dl} \times \vec{B}$.

Incorrect answers with minor flaws in vector thinking consisted of examples where students obviously attempted to solve the field as a vector, but they applied a combination of Tight-Hand Rule and trigonometry, resulting in confusion in the mathematics.

Incorrect answers with no vector thinking consisted of those where students computed the field as a scalar, *i.e*. they used the formula $B = \frac{\mu_0 I}{2\pi r}$ but without vector notations for each wire contribution and then added two scalars together as the resulting field. Some students used the RightHand Rule correctly in question b), but the magnitude of the field was already wrong.

Incorrect answers also consisted of empty answers to Part a) and scalar thinking in answer b).

The students' answers to the set of written test questions and the final exam problem indicate a relatively good performance in solving the problems involving magnetic field and magnetic force.

The instruction that needed to be implemented emphasized the use of vector formed relations as the primary method concerning magnetic field and force. In addition, the Right-Hand rules were supposed to be used only as a supportive tool for quickly determining the probable direction of the field and force. The vectors are, however, needed in order to calculate the exact values of superposed fields.

During the teaching intervention described in Appendix A the students found the repeated question "How do you apply the Right-Hand Rule?" quite quickly to be irrelevant and no longer of interest after they had produced the cross product in the referring relation. After completing the first few tasks, the students also tended to answer the questions concerning showing the directions and ranking the order of magnitudes based solely on the vector relations.

Some students argued that to explain the vector point of view in learning the Right-Hand Rule at upper secondary school should be: *"prevent them from misconceptions or at least insufficient conceptions in the first place"*.

IV. CONCLUSIONS AND IMPLICATIONS

In this study we implemented and evaluated a teaching sequence in magnetostatics. More precisely, we focused on the features of the Biot-Savart law and magnetic force law, paying particular attention to the instruction aimed at their physical explanation. The design of the teaching sequence was based on the Educational Reconstruction method. This method provides the tools for assembling the learning difficulties to be addressed, the analysis of content, and the teacher's perspective within a meaningful teaching event. The outcome of using Educational Reconstruction was a set of multi-step tasks. Evaluation of the teaching sequence was achieved using a baseline performance test and by designing challenging problems for the final exam.

The students' answers in the final exam problem clearly showed that they have adopted the desired vector thinking rather than simply using memorized rules. According to our findings, there was no sign of students falling wrongfully into the category of electric field analogy. This shows that the students had apparently abandoned that misconception. It also indicates that students are capable of adopting a correct concept once they have been able to apply a correct method that they understand in a more general and coherent way, thus enabling them to abandon their previous misuse of their initial concepts.

The students' positive response to the course of instruction and their relatively good results in the post-test and final exam can be explained by two arguments. The first is that the pre-test took place in a situation for which students had been unable to prepare in advance. They had forgotten or had only vague memories of what had been taught about magnetics, presumably a year or two previously in upper secondary school. The gap between success and failure in the pretest was narrow, and dependedon memorizing a few simple rules of thumb. Nevertheless, our recognition of the essential elements of the learning problems and our intentionally at designed instructional efforts to overcome them has turned out to be effective. The instructional intervention was, however, simultaneously intended to serve the needs of our learning goals, which in turn may be naturally more demanding than the teaching that students have received at the secondary level. The most important addition to what the students had previously learned and the key to their understanding further topics to be introduced in the course on electromagnetics was the introduction of the concept of vectors. McDermott has reported a similar two-step process in the case of introductory electricity – moving from recognition of the learning difficulty to the design of instruction on that basis [16, 17]. Instead of designing a teaching sequence, however, McDermott used particular tutorials, which we consider to eventually serve the same purpose.

Although a familiar problem, the jump from the preceding educational level to university level in physics, the proposed solutions have not been reported widely. Students taking the first-year physics curriculum are fully occupied in attempting to achieve the required understanding of physics and mathematics. Chabay's analysis of the learning problems connected with magnetostatics suggests a need to restructure the sequence of the introductory course in such a way that there would be other topics between the sequences of teaching the field and force concept. In addition, Chabay suggests that the field concept should be taught first so that early introduction of the concept of magnetic field will allow students to use the magnetic field of moving charges as a test of the current in electric circuits. Furthermore, magnetic field can also be viewed operationally as a field that affects a compass [9]. Chabay's sequence is, then, that field should precede force. This choice accords with our own analysis involving use of the Educational Reconstruction model. All attempts such as this to make the learning slope gentler will be rewarded eventually by greater commitment on the part of students to their studies. Chabay's suggestion that this might be achieved by restructuring the sequences is likely to be productive, in addition to the by-product consisting of educational reconstruction that will help to link students' initial knowledge with the aims of more advanced instruction at university level.

It is our assumption that, as a result of the absence of vector treatment at the preceding educational level, students participating in introductory courses on electromagnetic should not be treated as "Amperian" thinkers. They are, however, familiar with the Right-Hand Rules that have to be taken into account as a solid foundation on which a cross production interpretation can be constructed. In fact, Guisasola [3] classified a small group of his students as belonging to the "Amperian" category by their ability to make correct predictions based on the use of the Right-Hand Rule. According to our findings, however, one should take cautiously students' responses to the simple, highly symmetrical cases where they can apparently correctly apply the Right-Hand Rule. More thorough information about students' real physical understanding in the domain of magnetic field and force would be revealed by studying cases where the Biot-Savart law and magnetic force law are applied in their vector forms. Asymmetrical cases such as these do not form a part of widely used baseline performance tests such as CSEM and BEMA [18, 19]. Our conclusion, or rather the implication for further research methods, is that students performance following instruction should be measured with more challenging test examples than at the start of the course. After all, we expect students to learn more effective methods in the process of learning physics and to understand more profoundly the topics that they have learned previously in a simpler form.

The significance of understanding magnetic field and force as postulated in the Biot-Savart law and magnetic force law is quite profound for a student's future learning. The chapters dealing with the fundamentals of magnetostatics will be followed by other topics such as Ampere's law, inductance and electromagnetic induction, for instance. Indeed, successful learning of these topics depends on the correct treatment of the phenomena and principles of magnetostatics in their teaching. In the main, we were influenced by students' vague understanding of the conceptual, graphic, and mathematical representations of magnetic field as a vector field in general at the start of a course. The use of the Right-Hand Rule with no underlying physical reasoning was found to be the most important common factor in existing misconceptions. In the course of this study we have shown that with an understanding of vector-formed relations the physics behind the thumb rules becomes a powerful tool of thinking, explaining and problem-solving. Emphasizing the vector character of magnetic field in the teaching is essential, since concepts in magnetostatics are generally field-related.

The next logical step would consist of another cyclic process of applying Educational Reconstruction in teaching Ampere's law.

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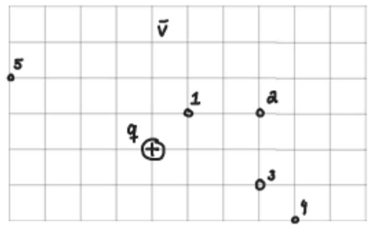
APPENDIX A GROUP S12. THE MULTI-STEP TASKS OF THE TEACHING INTERVENTION: MAGNETIC FIELD.

Moving charge/
along the page

1. Show the directions and rank in decreasing order the magnetic field strengths in the observation points 1...5

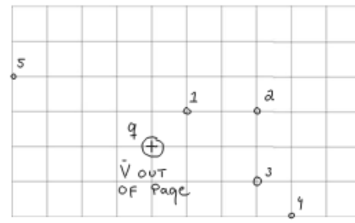


How do you apply $\vec{B} = \frac{\mu}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2}$

How do you apply the right hand rule?

Moving charge/
out of page

2. Show the directions and rank in decreasing order the magnetic field strengths in the observation points 1...5

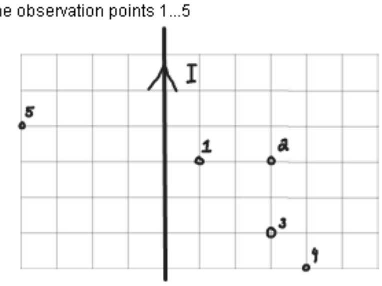


How do you apply $\vec{B} = \frac{\mu}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2}$

How do you apply the right hand rule?

DC wire/infinite
along the page

3. Show the directions and rank in decreasing order the magnetic field strengths in the observation points 1...5

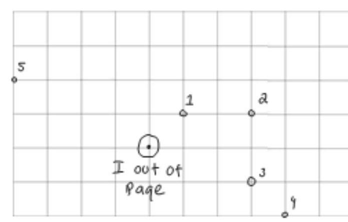


How do you apply $d\vec{B} = \frac{\mu}{4\pi}\frac{I\vec{dl}\times\hat{r}}{r^2}$ $B = \frac{\mu I}{2\pi r}$

How do you apply the right hand rule?

DC wire/infinite
Out of page

4. Show the directions and rank in decreasing order the magnetic field strengths in the observation points 1...5

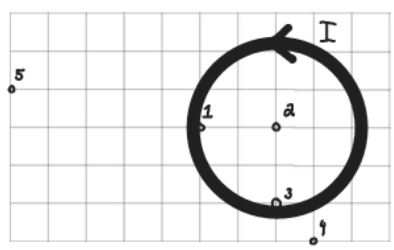


How do you apply $d\vec{B} = \frac{\mu}{4\pi}\frac{I\vec{dl}\times\hat{r}}{r^2}$ $B = \frac{\mu I}{2\pi r}$

How do you apply the right hand rule?

DC loop/
along the page

5. Show the directions and rank in decreasing order the magnetic field strengths in the observation points 1...5

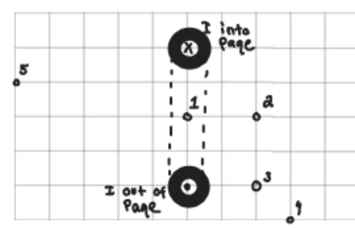


How do you apply $d\vec{B} = \frac{\mu}{4\pi}\frac{I\vec{dl}\times\hat{r}}{r^2}$

How do you apply the right hand rule?

DC loop/
perpendicular to
the page

6. Show the directions and rank in decreasing order the magnetic field strengths in the observation points 1...5

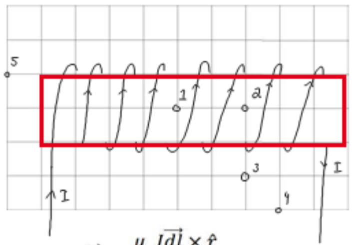


How do you apply $d\vec{B} = \frac{\mu}{4\pi}\frac{I\vec{dl}\times\hat{r}}{r^2}$

How do you apply the right hand rule?

solenoid

7. Show the directions and rank in decreasing order the magnetic field strengths in the observation points 1...5

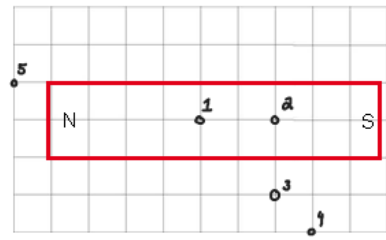


How do you apply $d\vec{B} = \frac{\mu}{4\pi}\frac{I\vec{dl} \times \hat{r}}{r^2}$

How do you apply the right hand rule?

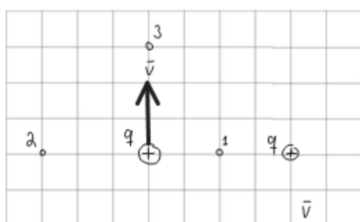
Bar magnet/
Side view

8. Show the directions and rank in decreasing order the magnetic field strengths in the observation points 1...5



Moving charges/
along the page

9. Show the directions and rank in decreasing order the magnetic field strengths in the observation points 1...3

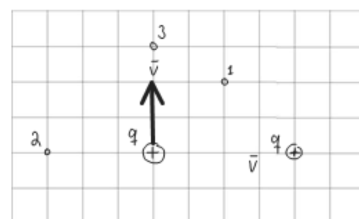


How do you apply $\vec{B} = \frac{\mu}{4\pi}\frac{q\vec{v} \times \hat{r}}{r^2}\bigg|$

How do you apply the right hand rule?

Moving charges/
along the page

10. Show the directions and rank in decreasing order the magnetic field strengths in the observation points 1...3

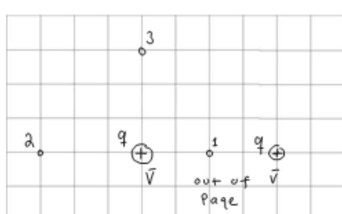


How do you apply $\vec{B} = \frac{\mu}{4\pi}\frac{q\vec{v} \times \hat{r}}{r^2}\bigg|$

How do you apply the right hand rule?

Moving charges/
out of page

11. Show the directions and rank in decreasing order the magnetic field strengths i the observation points 1...3

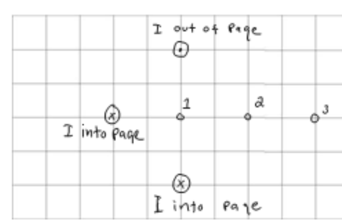


How do you apply $\vec{B} = \frac{\mu}{4\pi}\frac{q\vec{v} \times \hat{r}}{r^2}\bigg|$

How do you apply the right hand rule?

DC wire/infinite
in/out of page

12. Show the directions and rank in decreasing order the magnetic field strengths in the observation points 1...3



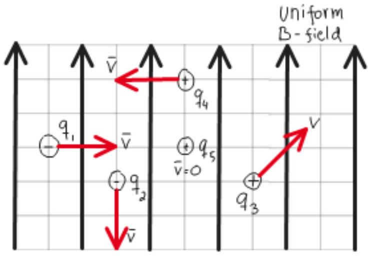
How do you apply $d\vec{B} = \frac{\mu}{4\pi}\frac{I\vec{dl} \times \hat{r}}{r^2}$

How do you apply the right hand rule?

APPENDIX A GROUP S34. THE MULTI-STEP TASKS OF THE TEACHING INTERVENTION: MAGNETIC FIELD AND FORCE.

Magnetic force/ identical charges moving with the same speed or v=0 along the page

13. Rank in decreasing order the magnetic force acting on the charges q1...q

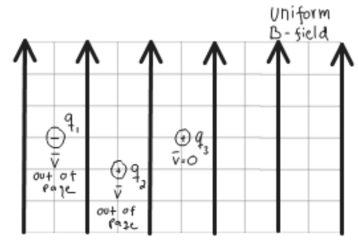


How do you apply $\vec{F} = q\vec{v} \times \vec{B}$

How do you apply the right hand rule?

Magnetic force/ identical charges moving with the same speed or v=0 out of page

14. Rank in decreasing order the magnetic force acting on the charges q1...q5

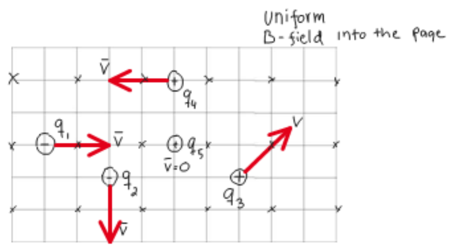


How do you apply $\vec{F} = q\vec{v} \times \vec{B}$

How do you apply the right hand rule?

Magnetic force/ identical charges moving with the same speed or v=0 along the page

15. Rank in decreasing order the magnetic force acting on the charges q1...q5

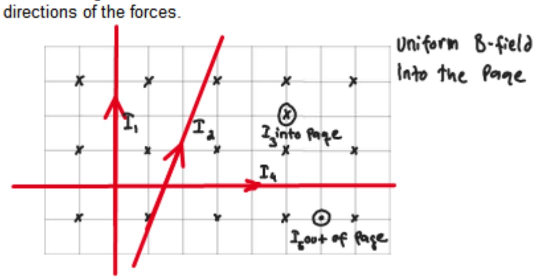


How do you apply $\vec{F} = q\vec{v} \times \vec{B}$

How do you apply the right hand rule?

Magnetic force/ infinite DC wires with the same I

16. Rank in decreasing order the forces actin on the wires 1...5. Show the directions of the forces.

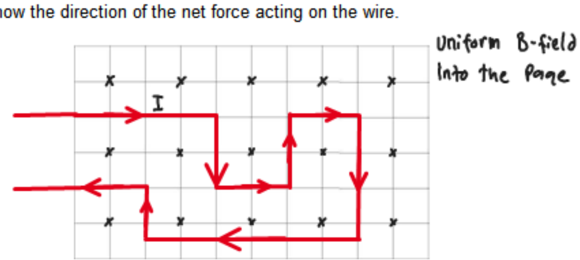


How do you apply $\vec{F} = I\vec{dl} \times \vec{B}$

How do you apply the right hand rule?

Magnetic force/ infinite DC wire

17. Show the direction of the net force acting on the wire.

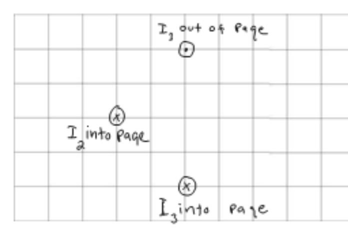


How do you apply $d\vec{F} = I\vec{dl} \times \vec{B}$

How do you apply the right hand rule?

The magnetic forces between the DC wires / same current into / out of.the

18. Show the direction of the net force acting on the wir
I_1



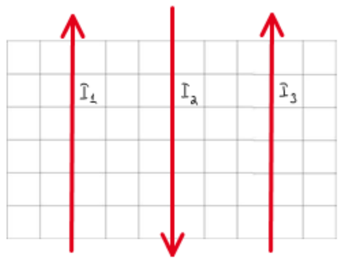
How do you apply $d\vec{F} = I\vec{dl} \times \vec{B}$ $\quad d\vec{B} = \frac{\mu}{4\pi}\frac{I\vec{dl} \times \hat{r}}{r^2}$

How do you apply the right hand rule?

APPENDIX A GROUP S34. THE MULTI-STEP TASKS OF THE TEACHING INTERVENTION: MAGNETIC FIELD AND FORCE.

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

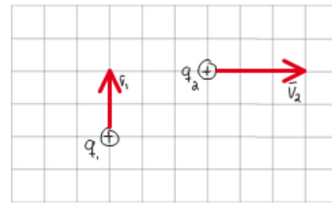


How do you apply $d\vec{F} = I\vec{dl} \times \vec{B}$ $\quad d\vec{B} = \frac{\mu}{4\pi}\frac{I\vec{dl} \times \hat{r}}{r^2}$

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?