

Introductory university physics students' understanding of some key characteristics of classical theory of the electromagnetic field

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(Received 25 July 2018; published 12 November 2018)

In this work, we explore how undergraduate students use classical field theory when describing physical phenomena in the context of introductory electromagnetism. We have extracted five key characteristics of the electric and magnetic field from a historical analysis of the topic. These characteristics informed the creation of a questionnaire comprising six free-response conceptual questions. The questionnaire instrument was administered to undergraduate students in three European countries. Phenomenographical analysis of the students' responses shows that many undergraduates do not have a coherent idea of field theory. We conclude that, rather than focusing on teaching rules with which to calculate, more attention should be paid to the specific characteristics of field theory and the difference between fields and forces, with particular emphasis on the conceptual interpretation of the interaction process.

DOI: [10.1103/PhysRevPhysEducRes.14.020117](https://doi.org/10.1103/PhysRevPhysEducRes.14.020117)

I. INTRODUCTION

Describing how objects interact with each other is a fundamental concern in physics. While Newton's force theory (objects interact by exerting forces on each other directly) is still useful today, field theory provides the best description at present. When teaching introductory electromagnetism, the discussion of field theory can often be limited to the definition of vector fields. Mathematically, a vector field is a physical quantity that can be described by assigning a vector to every point in space. Conceptually, a vector field describes how an object makes its presence felt by influencing the space surrounding it; this influence in space may then be felt by a second object. In this way field theory describes interactions between objects. It is more abstract than the Newtonian theory that is based on forces only, but has greater explanatory power (see, e.g., Ref. [1]).

Previous studies on students' understanding of electric and magnetic fields at secondary and undergraduate levels have reported widespread confusion and alternative conceptions of field and force that start at high school and

persist at the university level [2]. Specifically, students have difficulty in linking phenomenology (i.e., observable electromagnetic interactions) to the theoretical aspects that explain the observable changes in terms of fields. Researchers have reported that many students reason as if fields are identical to forces when asked to explain unfamiliar electric and magnetic phenomena [3–10]. It has been suggested that many students use a particle-based Newtonian conceptual profile, and that adoption of a source- and field-based Maxwellian profile could resolve these problems [4,9].

In this paper, we explore the explanatory ideas of university students from three different European countries about the field concept in electromagnetism. We have diagnosed students' ideas through a questionnaire that comprises six conceptual free-response questions. As our conclusions are based on responses from students in three different educational settings, they are likely to be widely applicable, as they are not tied to one instructor or even one educational system.

In Sec. II we describe the epistemological development of the field concept, and to what extent this is and should be reflected in textbook introductions. In Sec. III we explain the context and methodology of our study in detail. In Sec. IV we show the initial design and refinement of the questionnaire we used to probe our students' ideas about electric and magnetic fields. In Sec. V we summarize the results and implications for teaching.

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II. EPISTEMOLOGICAL DEVELOPMENT OF THE CLASSICAL THEORY OF THE ELECTROMAGNETIC FIELD

By the end of the 18th century the Newtonian world view held sway [11,12]. In the context of gravity, the Newtonian world consisted of extended hard bodies interacting through instantaneous, central action-at-a-distance forces through empty space. Gravitational interactions were described in terms of forces obeying an inverse square law. Laplace and others had developed the notion of a field as force per unit mass, but employed it purely as a mathematical tool [1].

Toward the final third of the 18th century attempts were made to provide the study of electricity with similarly quantitative foundations. Researchers such as Cavendish, Priestley, and Coulomb looked for a theory similar to gravitation, under the clear influence of Newtonian mechanics [13]. Coulomb's experimental results allowed retention of the Newtonian world view (albeit with the introduction of repulsive forces), and Poisson's description of electric fields mirrored Laplace's treatment of gravitational fields [14]. The noncentral character of the magnetic force discovered by Oersted and Ampère was one of the phenomena that spurred Faraday on to imagine a role for the surroundings in which the interaction took place. Further new experimental facts such as the finding that containers with air pressure maintained the charges better on a conductor; the influence of arranging different materials in Voltaic piles; the discovery of electro-optic and magneto-optic and electrochemical phenomena all lent credence to the notion that the space between charged bodies ("the medium") must be given a prominent role [1]. A second driving force for the development of field theory came from the search for underlying unity of natural forces, culminating in the law of the conservation of energy formulated in 1840 [15].

Thus, throughout the 19th century a shift away from a Newtonian world view took place, even though for a long time there was no experimental evidence to favor one view over the other. Up until that time, the development of field theory involved epistemological changes in reasoning and axiological changes with regard to goals and interests adopted by the scientific community. The experimental confirmation that electromagnetic waves travel at the finite speed of light by Hertz gave the first experimental confirmation that field theory was able to predict phenomena that force theory could not. To be consistent with mechanics, linear and angular momentum were ascribed to the field so as to not violate momentum conservation [16]. In the theory of special relativity instantaneous action at a distance is ruled out, and the field concept is necessary and not merely convenient for calculations [17]. The modern view of (nonquantum) fields is often referred to as Maxwellian, since it is close to Maxwell's mature world view.

A recurring topic of discussion in the theoretical framework of physics is the use of the Newtonian and Maxwellian models in interpreting electromagnetic phenomena. The models can be considered as having different but not contradictory ontological and epistemological status when it comes to interpreting interactions between charges. In fact, the scientific community assumes both, while acknowledging the higher conceptual level and power of the Maxwellian model. Developing field theory requires previous acquisition of the Newtonian model: the electric field is introduced starting from knowing Coulomb's electric force model. However, what is often missing is explicit acknowledgment of the theoretical insufficiencies of the Newtonian model.

The above discussion of the historical development provides important hints as to where students may have problems in the construction of concepts and theories. We have distinguished five key characteristics of the electrostatic and magnetostatic field that we deem relevant and attainable at the introductory university physics level (selected from characteristics identified by [1,14,15])

- KC1. The electrostatic field is produced by charges and the magnetic field is produced by moving charges (currents or magnets).
- KC2. The concepts of force and field are different concepts, even though they are tightly connected.
- KC3. Fields exert forces only on their sources: gravitational fields exert forces only on mass, electric fields on charge, magnetic fields on moving charge.
- KC4. There is no "self-interaction," that is, the electric field created by a point charge or the magnetic field created by a moving charge does not exert a force on that position.
- KC5. Changes in the fields are not instantaneous but propagate at the speed of the light.

While KC1–4 can be accommodated by Newtonian or Maxwellian models, KC5 only makes sense in a Maxwellian model. We feel that its inclusion in the introductory curriculum is not only desirable; it probably provides an important stepping stone towards understanding electromagnetic radiation, electro-optical and magneto-optical effects, and special relativity later in the physics curriculum. By contrast, electric and magnetic interactions are often introduced at the level of phenomenology see, e.g., Refs. [18–21]. In each of our universities, gravity has been introduced only in terms of force and not as a field [22]. Typically, electrostatic interactions are introduced first. The force concept is invoked to explain the electric interaction between stationary charges, followed by the definition of the electric field as the force per unit charge (often exerted by a larger charge on a smaller one, or its mathematical abstraction, the test charge).

At this stage the electric field is mostly a calculational convenience, and the Newtonian worldview is implicitly reinforced. Next, this electric field is used to define and

calculate the electric potential, sometimes in parallel with using the Coulomb force to calculate the electric potential energy, reinforcing the idea of force per unit charge exerted on a test charge. Then, suddenly, when introducing Gauss's law, the electric field is thought of as permeating space; test charges and forces are no longer invited to the party.

In this way the textbook approach to developing the theory of electric interactions superficially aligns with the historical development [23]. It is however bereft of conceptual or metaphysical resources that may help the student along the journey. The situation is less clear cut for magnetic interactions, where phenomenology is the starting point too, but the asymmetry between the source (a bar magnet or current-carrying wire) and the object experiencing the source (iron filings or compass needles) often results in a hybrid of force-based and source-based conceptualizations [24]. Moreover, because force and field are perpendicular, students are probably more aware that magnetic force and field are different entities.

III. CONTEXT OF THE STUDY AND METHODOLOGY

A. Introduction

In this study, we address the following research question: What are undergraduate students' understandings of electric and magnetic fields and their relation with the field theory? Most of the previous studies focus on the teaching and learning of the electric or magnetic field separately, with some exceptions [25,26]. In this study, we discuss the students' understanding of field theory during an introductory university electricity and magnetism course that includes the topics of the electrostatic field and stationary magnetic field [18,21,27,28]. Roughly speaking, we consider force-based and calculation-based reasoning Newtonian reasoning, and source-based or field-based reasoning Maxwellian. Of course, students may also use hybrid or incorrect reasoning, or they may apply ideas incorrectly or in an *ad hoc* manner.

The findings of this study contribute to the teaching of electromagnetism in the European countries where it has taken place (Spain, Belgium, and Ireland), but are also of international interest. Replication studies and planned cross-country studies, such as the research carried out by the authors on other subjects [29,30] and by other colleagues [31], suggest that, although there may be variations among individuals, there are common patterns of conceptual difficulties that appear in the group of students as a whole, regardless of differences in their educational system, and cultural background. These empirical studies are convergent with the psychological cognitive theory called phenomenography [32].

B. Context

This research was conducted with university students in first year physics courses in science and engineering at the

University of Leuven (KUL) and the University of the Basque Country (UPV/EHU), and with students in the second year of their physics, engineering, and science teaching degrees at Dublin City University (DCU). In each country, both the instruction and the questionnaire were given in the students' own language: that means Flemish in KU Leuven, Basque in UPV/EHU, and English in DCU. The questions were administered to 115 students from UPV/EHU, 100 students from KUL, and 114 students from DCU. All students had already studied the topic of electric field and magnetic field in their physics lectures. Moreover, all participating students had taken at least two years of physics in high school, with the exception of a small fraction of the DCU students. The UPV/EHU students had passed the national standard exams in Spain to enter University to study science or engineering. They received 3.5 h of lectures on electromagnetism and 2 h in the laboratory per week, for 14 weeks, in the second semester of their studies. KUL students had 4 h of lectures a week, and 2 h of recitation for 10 weeks in the second semester of their studies. At Dublin City University, the schedule comprised 1 h of lectures and 2 tutorials per week. In all cases, lectures were given by experienced university physics teachers. The electromagnetism curriculum was similar to those followed in textbooks such as Giancoli, Young, and Freedman; Tipler and Mosca; or Fishbane *et al.* [18,21,27,28].

C. Data analysis

The students' responses to the questionnaire were subjected to a phenomenological analysis [33,34]. This type of analysis has been commonly reported in the literature in studies that attempt to describe the qualitatively different forms in which individuals conceive of various phenomena in physics [35–37]. Following this approach, the responses given by each participant were carefully studied to discern their conceptualization of field theory. We were able to construct a set of categories that describe the qualitatively different ways in which participants responded. The various categories that emerged from the data analysis were refined several times until a satisfactory final categorization was attained [38].

Following the criteria of Marton and Booth [33] for building categories, the analysis of the responses was performed at two levels with the following characteristics: (a) each category tells us something distinct about a particular way of experiencing the phenomenon, (b) the categories are hierarchical, and (c) there are as few categories as is reasonably possible. The first level of categorization refers to students' understanding on their own terms; the second level analyzes the students' understanding in terms of the congruence of their answers with accepted scientific ideas. In both cases, data analysis takes place at the collective level, with an emphasis on inter-individual rather than intra-individual variation.

TABLE I. Key concepts addressed by the questionnaire.

	KC1: sources	KC2: force/field	KC3: own source	KC4: no self-interaction	KC5: propagation
Electric Field	✓	✓		✓	
Magnetic Field	✓	✓	✓	✓	
Magnetic Force	✓	✓		✓	
Magnetic Needle	✓		✓		
Sudden Charge					✓
Broadcast					✓

In the first phase, our analysis centered on twenty responses from each university. The researchers in each university carefully read the responses and paid close attention to identifying statements that revealed student reasoning (first level of analysis). The responses were then compiled to form a set of quotes, which served as a basis for the development of tentative categorization schemes. Two categorization schemes evolved: one for the description of student explanations in general (the first level of analysis), and the other based on the alignment of the responses with field theory (the second level of analysis). In each case, the coding scheme included various categories illustrated by typical student statements, and the underlying logic in classifying each statement in the corresponding category. During this process, the research team held a series of discussions in which consensus was reached on data interpretation. During these discussions the categories were revised and refined a number of times to increase their fit with the students' responses from all universities. This categorization scheme was then applied to the remaining responses. It was found to be adequate to describe those responses as well. In each case, fifteen percent of the questionnaire responses were categorized independently by two members of the research team, and we derived a high degree of agreement (89%). At this stage only minor modifications were introduced to adjust the scope of the categories. The remainder of the questionnaires were categorized independently at each university. Finally, a meeting was held to check together the classification of the answers from each university and to discuss some answers that were difficult to categorize (about 5% of the total). In those cases, the consensus was reached through arguments based on the evidence of written answers.

IV. DESIGN OF THE QUESTIONNAIRE

This study investigates two different but related types of understanding of electromagnetic field theory. These are the ability to express scientific knowledge (e.g., facts, concepts, and interpretation) and using this knowledge to generate explanations of phenomena in different contexts (here, electricity or magnetism). To this end, we designed a questionnaire comprising six conceptual free-response questions about electromagnetic phenomena. Each question leaves students free to select the appropriate concepts

to develop their explanations. As the questions are focused on inquiring students' understanding, they are not mathematically complex, since mathematical difficulties may mask conceptual difficulties.

We have labeled the six questions that make up the questionnaire Electric Field, Magnetic Field, Magnetic Force, Magnetic Needle, Sudden Charge, and Broadcast. The Electric Field, Magnetic Field, Magnetic Force, and Magnetic Needle questions address KC1, KC2, and KC4; the Magnetic Field question also addresses KC3. The Sudden Charge and Broadcast questions address KC5. Table I shows which key concepts each question addresses.

The *Electric Field* question (Fig. 1) has two main purposes: to see whether students distinguish between force and field (KC2) and whether they understand that a charge does not act at the place it is located (KC4). This question is based on item 1 of the study by Furió and Guisasola [4]; it was slightly reworded and redrawn. Possible interpretations of the question were discussed, and a small pilot study was carried out with a small sample of students in the three universities. These students typically had no difficulty in understanding the questions.

The *Magnetic Field* question (Fig. 2) is original to this study. Its objective is twofold. It checks if students realize that only moving charges create a magnetic field (KC1); and specifically, that only the current in the wire generates a magnetic field at point P (KC4). Since the source of the field does not change, the field itself is unchanged though the force varies (KC2). Thus, as in the Electric Field question, the field vector is the same as in Fig. 1(a).

From a pilot study with a small student sample from different universities we gleaned that the perspective of the drawing is important. In an earlier version the loop did not look to be perpendicular to the wire, and the magnetic field

The electric field E due to a charge Q at a point P is represented in Figure 1a. What would be the representation if a very small negative charge is placed at point P (see Figure 1b)? Draw this representation and explain your answer.

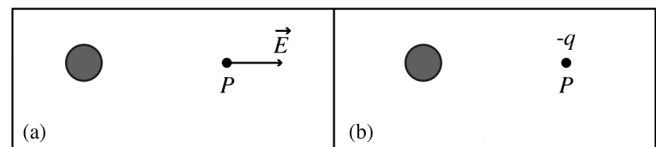


FIG. 1. The Electric Field question, based on item 1 in Furió and Guisasola [4].

A wire carries a current I . The magnetic field at point P is drawn in the x -direction; see figure (a). Two new situations are shown: (b) there is a static tiny positive charge q at point P and (c) there is a tiny positive charge q moving with speed v in the z -direction. Draw the magnetic field vector at point P in situations (b) and (c). Explain your answer.

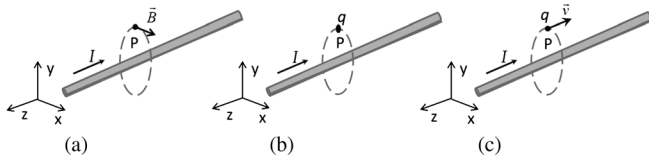


FIG. 2. Final version of the Magnetic Field question designed by the authors of the paper.

A wire carries a current I . Nearby, a positive charge q is moving with speed v parallel to the wire (see figure). Draw the magnetic force acting on the charge at point P .

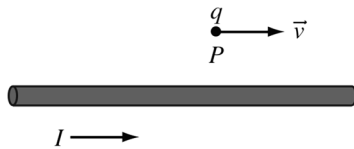


FIG. 3. The Magnetic Force question, designed by the authors of the paper.

did not look tangential to the loop, to all students. Figure 2 shows the adapted drawing.

The *Magnetic Force* question (Fig. 3) also aims to establish students' understanding of the difference between force and field (KC2). No explicit mention is made of the magnetic field, but students need to use the concept to answer the question. The question also determines the fluency of students in applying the cross product or right-hand rule. The pilot study showed that students understood the question and had no difficulties with interpreting the question. This question has remained unchanged.

The *Magnetic Needle* question (Fig. 4) was based on item 3 of Guisasola *et al.* [39]. The question was reworded and a sketch of the situation was added. Again, the question asks about force; in this case, students can answer the question without thinking about the field explicitly. There is no magnetic interaction between the magnetic needle and the stationary charge, since the magnetic field of the needle (caused by the magnetic dipole moment associated with the spin of unpaired electrons) only acts on moving charges (KC3). Students may consider that the magnetic needle will be electrically

A magnetic needle is initially pointing north as seen in the figure. A charge $+Q$ is then placed nearby. Describe what kinds of forces, if any, the needle and the charge exert on each other. Explain your answer.



FIG. 4. The Magnetic Needle question. Adapted from item 2 of Guisasola *et al.* [39].

A small charge q is placed at some distance from a charge Q . Will the forces that both charges exert on each other appear at the same instant q is positioned? Explain your answer briefly.

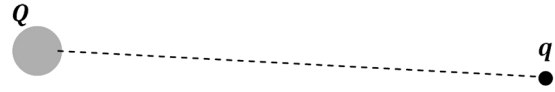


FIG. 5. The Sudden Charge question, adapted from item 2 in Furió and Guisasola [4].

You are watching on a television a soccer match broadcast from Argentina. Are the images recorded in Argentina shown at the same instant on your television in Dublin? Justify your answer.

FIG. 6. Final version of the Broadcast question, designed by the authors of the paper.

polarized, and thus state that there is an electric force. This would be considered excellent reasoning, beyond expectation in fact; two students gave this response. A pilot study at EHU showed that students understood the question well.

The objective of the *Sudden Charge* question (Fig. 5) was to assess the students' understanding of the non-instantaneous character of the electric interaction (KC5). This question was based on item 2 from Furió and Guisasola [4]. The original phrasing ("At some distance from a charge Q we place a small charge q . Will the forces that exert both charges appear at the same instant q has been placed, or after a short time?") proved ambiguous to our cohort of students: a significant fraction of students stated that while q was being moved into place, things were changing. This is in itself interesting, but does not probe what we want. We rephrased the question so that a charge would appear suddenly.

Finally, the *Broadcast* question (Fig. 6) presented students with an everyday phenomenon. It is possible to answer this question correctly (electromagnetic field propagation is not instantaneous, KC5) using an incorrect model, e.g., transmission of an image as a quasiobject which "obviously" takes time to travel. In the pilot study, we found that students understood the question, and it was not adapted.

V. RESULTS

To explore the progression of students' explanations of field theory from electricity to magnetism, we present electricity and magnetism questions together. We show typical explanations for each category. First, we describe our students' explanations about the electric and magnetic fields and its effects (characteristics KC1–KC4). Second, we present the students' ideas on the source of the magnetic field (characteristics KC1 and KC3). Finally, we analyze students' ideas about the propagation of interaction in the electromagnetic field theory (characteristics KC5).

A. Students’ ideas about field and force

The Electric Field, Magnetic Field, and Magnetic Force questions all probe KC1 (sources), KC2 (force vs field), and KC4 (no self-interaction). On analyzing the students’ answers, four main categories emerged: (A1) essentially correct answers based on Maxwellian reasoning; (A2) essentially correct answers based on Newtonian reasoning; (B1) confusion between force and field; (B2), at the same hierarchical level as B1, self-interaction in the form of a field due to the charge at its own location, either on its own or added to the original field. The same categorization could be applied across the three questions, if we accept that the Magnetic Force question does not allow us to distinguish between correct Newtonian and Maxwellian reasoning. Table II shows the categorization and prevalence of students’ answers.

If both types of reasoning occurred in an answer, we assigned it to the category that seemed most strongly emphasized; if there was no difference, we put it in the category that occurred first. Examples of responses in category A1 are as follows:

“Direction of electric field is the direction a positive test charge would move in if released at that point, so putting a negative test charge at that point doesn’t change direction of field. And $E = F/q$ so the charge of the test charge ($-q$) won’t change the magnitude.” (Electric Field question, DCU student 11).

“At point P, the field of the charge $-q$ is zero, so the field stays the same.” (Electric Field question, KU Leuven student E13)

“The electric field stays the same, it only depends on Q.” (Electric Field question, KU Leuven student E87)

“The magnetic field in cases b and c are the same as in case a, because the magnetic field is $B = \mu I/2\pi r$ in point P. The charge q moves but does not affect the field in point P.” (Magnetic Field question, UPV/EHU student 52)

“The magnetic field is still moving in the same direction as in (a), because although a magnetic field is induced by moving charge q, the new magnetic field has no vector at point P, as shown in my diagram on the left.” (Magnetic Field question, DCU student 2)

“The magnetic field caused by the current in the wire is always the same, independent of the charge nearby. Only two magnetic fields can mutually interact.” (Magnetic Field question, KU Leuven student M46)

“The magnetic field is independent of a charge moving in it.” (Magnetic Field question, KU Leuven student M95)

The first response above shows both types of reasoning; we felt that Maxwellian source-based reasoning was more important to this student than the calculation, which seemed to be provided as additional evidence.

Examples of responses in category A2 are as follows:

“The electric field is defined as $E = kq/r^2$. As the charge Q and the distance don’t vary the field E is the

TABLE II. Categories of answers and prevalences for the Electric Field, Magnetic Field, and Magnetic Force questions.

Category	Electric Field question			Magnetic Field question			Magnetic Force question		
	UPV/EHU (N = 115) [%]	KUL (N = 100) [%]	DCU (N = 114) [%]	UPV/EHU (N = 115) [%]	KUL (N = 100) [%]	DCU (N = 56) [%]	UPV/EHU (N = 115) [%]	KUL (N = 100) [%]	DCU (N = 56) [%]
A1. Correct Maxwellian understanding of the source of field and the relation between force and field	17	29	11	26	41	18	38	50	14
A2. Correct Newtonian understanding of the source of field and the relation between force and field	4	13	4	22	15	5			
B1. Misunderstanding of the relation between force and field	39	35	38	12	9	0	26	13	25
B2. Superposition or self-interaction	9	1	23	20	9	45	12	11	14
C. Incoherent (rote learning and wrongly assimilated)	13	13	26	5	10	23	11	1	11
D. No explanation or no answer	18	9	0	21	16	7	13	25	36

same. The test charge $-q$ does not generate a field at point P since the distance is 0. Therefore, the vector drawing is the same as in Fig. 1(a).” (Electric Field question, UPV/EHU student 2).

“Electric field is independent of q . $E = F/q$.” (Electric Field question, DCU student 45)

“The E vector remains the same but the force changes, because $E = F/q$.” (Electric Field question, KU Leuven student E2)

“I think that the magnitude of these two vectors should be the same because as you can see from [the Biot-Savart Law] the magnetic field vector is independent of the velocity of q and since I in each case is equal, they should be equal.” (Magnetic Field question, DCU student 12)

“The electric field vector is—according to the convention—always like the effect on a positive test charge. The force by Q on $-q$ however is in the other direction.” (Electric Field question, KU Leuven student E22)

The second quote above did not mention sources; because of this, and its brevity, we felt it was more likely to be Newtonian than Maxwellian in character. The third quote is deemed Newtonian, since it is firmly rooted in calculation. The fourth and fifth quotes we see as more likely to be Newtonian than Maxwellian: even though they mention I and Q , respectively, they are not explicitly identified as the field sources, and the reasoning appears to be algebraic.

For the Magnetic Force question, examples of responses in joint category A are as follows:

“The B field generated around a conductor (a current) is determined by the right-hand rule and can be drawn as pointing out of the paper. Moreover, the Lorentz force exerted on the moving charge is $\vec{F} = q\vec{v} \times \vec{B}$ and so again with the right-hand rule the direction of the force is determined (vertically downward in the drawing).” (Magnetic Force question, UPV/EHU student 29).

“The force is perpendicular to the field and the velocity. The direction of the field is determined by the RHR. (Force correctly drawn)” (Magnetic Force question, KU Leuven student M74)

In the Magnetic Field and Magnetic Force questions, some of the correct answers were justified by quoting the right-hand rule without mentioning the characteristics of the field theory explicitly, as in the last two quotes shown. While it may seem generous to consider these correct explanations along the lines of field theory, category A is a better fit than category B1 or B2. It is hard to see how a student could come to a correct answer that involves the magnetic field without implicitly using the Lorentz force, and thus distinguishing between force and field. This type of answers could be given by students who hold a Maxwellian or a Newtonian view.

For the Electric Field question a typical answer in category B1 incorrectly states that the field vector points

in the opposite direction (i.e., in the direction the force vector would point). Similar answers are also prevalent in the study of Furió and Guisasola [4] carried out in Spain, the study of Garza and Zavala carried out in Mexico [40], and the studies of Maloney *et al.* [41] and Planinic [42] with American and Croatian students. In the magnetism questions the answers in category B1 are split between those that state the magnetic field vector and the magnetic force have the same direction and those that confuse force and field. Examples of answers in category B1 are as follows:

“If we put a negative charge close to the positive, it will be attracted to it. The vector changes.” (Electric Field question, UPV/EHU student 79)

“This is a moving charge [that] will create current which will in turn give rise to a magnetic force which will alter the way \vec{B} is pointing.” (Magnetic Field question, DCU student 16)

“Positive and negative charges attract each other (draws vectors showing attraction).” (Electric Field question, KU Leuven student E23)

“The electrical field always starts from a positive charge Q , and arrives at a negative charge. So, if Q is positive, than it will attract the charge $-q$ (in point P) by E .” (Electric Field question, KU Leuven student E3)

“The electric field is the force that a positive test charge would feel in space. As the charge in point P now is negative, the force must change direction.” (Electric Field question, KU Leuven student E48)

“For b: the charge is at rest. As the force of the magnetic field is determined by the velocity, it will be zero (draws no B -vector). In c, the charge has a velocity, so there will be a force on the charge.” (Magnetic Field question, KU Leuven student M55)

Category B2 comprises responses in which students see the field generated by the small charge either as the only field experienced by the small charge or as added to the original field. In the Magnetic Field question, almost all responses in this category state that the magnetic field is unchanged when the charge is stationary, but that there is superposition for the moving charge. Some typical responses in this category are as follows:

“A negative charge will generate an electric field [that] flows in the -ve direction compared to the field due to the charge Q at P . This electric field will cancel or reduce the electric field at P when the small charge $-q$ is placed at P . The electric field [vector] will only get a little shorter as the charge $-q$ is very small.” (Electric Field question, DCU student 54)

“The force will be the sum of the force made by the magnetic field produced by the current of the wire and the magnetic field produced by the moving charge. The forces are in the same direction.” (Magnetic Force question, UPV/EHU student 83)

A small number of students (typically fewer than 10%) explained that field lines exert a force on the test charge in answering the Electric Field question; this answer did not occur for the two magnetism questions. For example,

“If we put a negative charge close to the positive, the electric field lines of charge Q will attract it.” (Electric Field question, UPV/EHU student 93)

This type of explanation also appears in the works of Törnkvist *et al.* [43] and Pocić and Finlay [44]. We have incorporated these answers in the next category in the hierarchy “incoherent answers.” While a considerable fraction of answers in this category contain confused ideas, some may be just a brief clarification short of fitting into category A, B1, or B2. The quote below gives an example of the latter. The correct answer is given, so the student may well have meant something like “the test charge has no impact on the magnetic force whether it has a speed or not,” but we cannot be sure.

“(b) the magnetic field vector is the same. (c) the magnetic field vector is the same. Speed has no impact on the magnetic force.” (Magnetic Field question, DCU student 13)

The different prevalences of answers between the three universities is striking. It is not our intention (nor is it possible) to try and explain these differences; the salient information is that the categorization works even if the frequency of occurrence varies greatly.

A small fraction of the students recognized the distinction between electric field and electric force; in all three universities more students gave correct responses to the Magnetic Field question than to the Electric Field question.

B. Students’ ideas about sources of magnetic and electric fields and how they act on them

The main objective of the Magnetic Needle question is to investigate students’ understanding of the source of electric and magnetic fields (KC1), and that the fields act only on their sources (KC3). We summarize the results in Table III.

Students from the three universities answered the question similarly. About one-third of the students recognized in

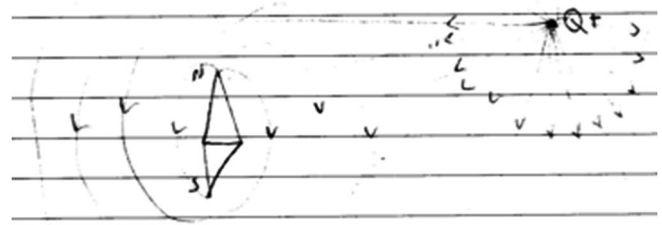


FIG. 7. Magnetic Needle question, DCU student 12.

this context that charge at rest is not a source of magnetic field and that the field cannot act on it (category A). Some examples of responses included in this category are as follows:

“The Q charge is at rest and therefore the magnet exerts no force on it.” (Magnetic Needle question, UPV/EHU student 49)

“There is no force. The charge is at rest. $\vec{F} = q\vec{v} \times \vec{B} = \vec{0}$.” (Magnetic Needle question, KU Leuven student M53)

“The needle is slightly magnetized and so will generate a magnetic field which extends to the charge $+Q$. The $+Q$ charge will be generating an electric field, with electric field lines moving away from the charge. However, since both the charge and the needle are stationary there will be no interaction between the two objects.” (Magnetic Needle question, DCU student 51)

About half of the responses fall into category B. In some cases students seem to associate a positive charge with the magnetic North pole, in which case they misunderstand the source of the magnetic field (KC1):

“Yes they exert forces on each other, the charge will create an electric field as shown above (Figure 7), and the magnetic needle will create a magnetic field also as shown. So in turn there will be a magnetic force acting on the charge and vice versa”. (Magnetic Needle question, DCU student 12)

“The compass has the positive side at the north pole and the south pole is negative, as the charge Q is positive it will repel the north pole of the compass.” (Magnetic Needle question, UPV/EHU student 21)

TABLE III. Categories of answers and prevalences for the Magnetic Needle question.

Category	Magnetic Needle question		
	UPV/EHU ($N = 115$) [%]	KUL ($N = 100$) [%]	DCU ($N = 56$) [%]
A. Correct understanding of the field sources	29	38	30
B. Misunderstanding of the magnetic field source	54	44	50
C. Incoherent	5	11	13
D. No explanation or no answer	12	7	7

TABLE IV. Categories of answers and prevalences for the Sudden Charge and Broadcast questions.

Category	Sudden Charge question			Broadcast question		
	EHU ($N = 115$) [%]	KUL ($N = 100$) [%]	DCU ($N = 60$) [%]	EHU ($N = 115$) [%]	KUL ($N = 100$) [%]	DCU ($N = 56$) [%]
A1. Noninstantaneous, Maxwellian	5	4	20	11	31	36
B1. Instantaneous, field is already there	19	12	23	0	0	0
B2. Coulomb's law or Newton's 3rd law	30	34	10	0
C1. Noninstantaneous, it takes time to do something	3	11	5	19	16	46
C2. Instantaneous, it is a fact	15	14	23	46	31	0
Incoherent	17	20	15	13	11	13
No explanation or no answer	11	6	3	11	11	5

“The needle will begin to move towards the positive charge, as it is attracted to the positive charges of the north pole, it will also be attracted slightly to the +Q charge.” (Magnetic Needle question, DCU student 41)
“The north of the magnetic needle is positively charged. Two positive charges repel en so the charge and the magnetic needle will feel a repellent force.” (Magnetic Needle question, KU Leuven student M56)

This learning difficulty is also shown in the studies by Scaife and Heckler [26] and Jeličić *et al.* [45]. They found that some students believe that there are charges at the poles of a magnet, which can interact with charges at rest.

Some students seem to think magnetic fields act on the stationary charge, thereby not only acting on their sources (KC3). For example,

As in the previous question, about 20% of students do not answer or do so incoherently.

C. Students' ideas about the propagation of field

One of the key characteristics that distinguishes Maxwellian from Newtonian field theory is the finite speed and propagation time within the medium in which the interaction takes place (KC5). The Newtonian theory of force is instantaneous; Coulomb's law does not state the time it takes for interactions to occur. Maxwellian field theory on the other hand offers an explicit clarification and limits the interaction speed to that of light. The *Sudden Charge* and *Broadcast* questions probe this understanding (see Table IV).

The answers of a small fraction of students state the interaction time is determined by the speed of light, or are otherwise clearly grounded in field theory (category A1). For example,

“No, because the sphere first has to cause a change in its surroundings (medium) and that change has to propagate through the medium until it reaches that

part of the medium which is around the test charge q_1 .” (Sudden Charge question, DCU student 53)

“The forces cannot appear at the same instant as the charge is changed, because the electric field from Q cannot extend from Q faster than the speed of light.” (Sudden Charge question, DCU student 16)

“The electromagnetic waves propagate at the speed of light. Images cannot be simultaneously in Argentina and in Dublin.” (Broadcast question, UPV/EHU student 8).

“Electromagnetic waves need some time to propagate. The time it takes is very small but not instantaneous.” (Sudden Charge question, UPV/EHU student 52)

“The images are sent at the speed of light, so there will be little bit of delay.” (Broadcast question, KU Leuven student M79)

“The electric field ‘fills’ the space with the velocity of light, the force therefore will—at short distances—act almost immediately.” (Sudden Charge question, KU Leuven student E8)

At the next level, we again discern two categories. Answers in category C1 use nonscientific reasoning in justifying that the interaction is noninstantaneous. Some typical examples:

“Yes, if the distance is big, the TV images need time.” (Broadcast question, UPV/EHU student 39)

“No, electromagnetic waves have to go to the satellite and time is wasted. We do not have the technical means for instant transmission.” (Broadcast question, UPV/EHU student 14)

This kind of answer is much more prevalent for the *Broadcast* question. We think it likely that the Science-Technology-Society context is a contributory factor, and students may have heard of a delay in transmission. The setting is also less likely to trigger students to think of a “Newtonian” law like Coulomb's law.

Answers in category C2 state that the interaction is instantaneous, more or less as a statement of fact:

“Yes, the electric force is simultaneous because when the sphere is charged, an electric field is created and, at the same instant, it acts on the charge q .” (Sudden Charge question, UPV/EHU student 16)

“Yes, because television images are everywhere at the same instant.” (Broadcast question, UPV/EHU student 14)

These types of arguments are based on a methodological misconception about the relations of induction between the experimental facts and the theory [41,42]. They start from an erroneous perception of the experimental fact.

VI. CONCLUSION AND EDUCATIONAL IMPLICATIONS

Based on a review of the historical development of electric and magnetic interactions from the Newtonian force to the Maxwellian field theory, we have selected five key characteristics of field theory we deem relevant and attainable for introductory university physics courses. In this study we investigate students’ ideas about the field concept in classical electromagnetism. To this end, we have analyzed the answers of students from introductory physics courses at three different European universities to six conceptual free-response questions that probed their ideas about electric and magnetic fields. We were able to assign the answers into a small number of hierarchical categories.

Regarding the research question on exploring to what extent students in introductory courses learn a scientific model of the electromagnetic field, the results of the study show that most students do not have coherent conceptions of field characteristics. Some of the students’ explanations reflect Newtonian or Maxwellian thinking, sometimes they apply one kind of reasoning to answer one question and then change tack, and in other cases they indicate confused or incorrect and *ad hoc* reasoning. For each of the Electric Field, Magnetic Field, and Magnetic Force

questions, only a small fraction of students reasoned correctly and in accordance with the Maxwellian model (category A1). Another small fraction of students reasoned correctly and in accordance with a Newtonian view (category A2). In almost all questions the most common responses reflected confusion between force and field or about the source of the fields. Incorrect application of Newtonian ideas and partial understanding of Maxwellian concepts were also common. The answers of many students were not based on scientific reasoning. Rather, reasoning tended to be restricted to applying rules of the theory, even if those rules were erroneously perceived to begin with by the students.

The responses to the Sudden Charge and Broadcast questions provide further evidence in support of this view. In these questions the students are not explicitly asked for a scientific explanation and so the questions probe their spontaneous reasoning. A significant fraction of students’ responses are based on fact or justification rather than elements of field theory (categories B2, C1, and C2).

The picture that has emerged is that few students use field theory explicitly or implicitly, and among those that do, many do not have a coherent picture of force and field. Clear evidence for this statement can also be found in the response to the Magnetic Needle question, where many students do not understand the nature of the source of the magnetic field and either argue that the needle contains charges at the poles, or that the magnetic field affects the static charge. It appears that in this case students attempt to reason based on field theory, but misunderstand a key characteristic and so cannot predict the phenomenon correctly.

In conclusion, we believe that more attention should be paid to the specific characteristics of field theory and the difference between fields and forces, with particular emphasis on the conceptual interpretation of the interaction process rather than rules. Such an approach would guide students in the transition from a Newtonian to a Maxwellian viewpoint, underpinned by a changing view of the field from a calculational convenience to a physical entity.

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