How do undergraduate students understand the displacement current and apply Ampère-Maxwell's law?

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Abstract. We investigated the learning difficulties of second-year (university) students in electromagnetism courses when applying the Ampère-Maxwell law. We analyzed the written responses of 65 students using phenomenography and supplemented our investigation with 12 interviews. The results revealed that students apply the Ampère-Maxwell law by rote, they believe that it can only be used to calculate magnetic fields when the curve used is symmetrical and they do not consider the shape of the magnetic field lines when applying it.

Introduction

Incorporating Maxwell's displacement current into Ampère's law was a milestone in developing the electromagnetic theory. This generalization was the culminating point in the development of the theory. In the context of Physics Education Research, many investigations have been carried out to address students' difficulties related to electromagnetism, for example, those focused on Gauss, Ampère, or Faraday laws [1, 2]. In contrast to these advances, studies dedicated to the Ampère-Maxwell's law and the displacement current have been more limited [3, 4]. Here, we report an investigation including fieldwork focused on students' difficulties in the displacement current and the application of Ampère-Maxwell's law.

Theoretical framework

We propose an epistemologically grounded approach to teaching that involves considering contributions related to the Nature of Science and its influence on teaching. Concerning its construction process, one major requirement is to detect key features of the epistemological development of theories the understanding of which can facilitate students' learning [5]. In this sense, we carried out an epistemological analysis of the development of classical electromagnetism and its culmination with the Ampère-Maxwell law, which allowed us to identify a set of key concepts for its understanding [4].

Methodology and findings

From the identification of the key concepts, we defined the learning objectives for the curriculum of the Ampère-Maxwell law in electromagnetism courses for Physics and Engineering undergraduate students. We selected one of the learning objectives: the correct application of the magnetic field circulation operator in the framework of the Ampère-Maxwell law and designed a question, shown in Fig. 1, to assess it.

The question is presented in figure 1. The students were asked to analyze the resolution and make a brief comment, explaining whether they agree or, if not, what modifications they would make. We proposed the question to 65 students of Physics degree courses belonging to the University of the Basque Country (Spain) and the University of the Republic (Uruguay). We analyzed the answers using phenomenography [6] and complemented our research with interviews to 12 students on the same question.

Question. The figure shows a uniform electric field increasing with time, confined to a cylindrical region of radius R. Agustina wants to determine the magnetic field at a point P located at a distance *a* form the center of the cylindrical region. Analyze the steps followed by Agustina in solving the problem and make a brief comment on each one, explaining why you agree or, if not, what modifications you would make.

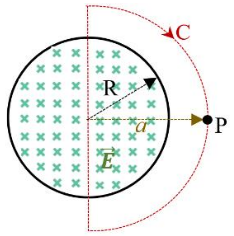

Fig. 1. Question proposed to the students.

When analysing the students' answers, we identified a set of categories that reflect different types of explanations (see Table 1). We identified student reasoning that could be related to both the rote application of the Ampère-Maxwell law and a functional fixation of the equation. These results reveal that students do not consider the shape of magnetic field lines when applying the law. In addition, we found that some students argued that the lack of symmetry of the curve did not allow the magnetic field to be calculated.

Table. 1. Answer categories and their percentages for the question

Category	Description of the category	%
A	They agree with the analysis	*15,4%*
B	They do not agree with the calculation of the magnetic field circulation.	15,4%
C	They do not agree with the election of the path claiming symmetry reasons.	20,0%
D	They mix up flux and circulation	6,2%
E	Incoherent.	9,2%
F	No answer.	33,8%

Conclusion

Our results allow us to conclude that students do not use the available information about the magnetic field when applying the Ampère-Maxwell law, nor do they recognize that the magnetic field circulation is a sum. They also highlight the importance of developing learning sequences that challenge students to calculate the field from the Ampère and Ampère-Maxwell laws using non-conventional curves as well as performing inverse problems where the magnetic field cannot be determined from the line integral. We will use these results to define the learning demands that will form the basis for the design of a future teaching and learning sequence.

References

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