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Learning interference between electricity and magnetism? Analysis of patterns and consistency

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Abstract

Due to the similarities between Gauss's and Ampere's laws, students can present cognitive interference when learning these laws in the introductory physics course. This study aims to analyze the interference patterns that emerge in students' answers when solving problems that involve Gauss's and Ampere's laws and related concepts (e.g., electric flux and magnetic circulation). We conducted a study of 322 engineering students attending a private Mexican university. We applied two open-ended questionnaires with questions that prompted using Gauss's and Ampere's laws. We analyzed students' answers to identify whether they presented some word or element of an equation from the opposite context and coded them into coding families. We analyzed the consistency of interference by counting the times each student presented some interference in general and by coding family. The results indicated that the interferences related to the shape of the Gaussian surface or Amperian trajectory and field-related concepts are shared among contexts. However, the interference related to the source of the field (charge or current) is predominant in magnetism. In contrast, the interference related to using elements from the opposite context in an equation predominates in electricity. In other words, students referred to currents as charges and wrote equations that contained B (for magnetic field) or other similar elements in Gauss's law. The general consistency analysis revealed that around half the students presented at least one interference in both contexts. We recommend that the interference between electricity and magnetism in Gauss's and Ampere's laws must not be overlooked. This study's findings can guide introductory and intermediate electricity and magnetism instructors to address this interference phenomenon.

Keywords: physics education research, electricity and magnetism, introductory physics, higher education, educational innovation, STEM education

INTRODUCTION

The concepts of electricity and magnetism are ontologically and epistemologically related, which can confuse students. An example of electromagnetic conceptual confusion is the misconception about charged poles, where students attribute a positive charge to the magnetic north poles (Maloney, 1985). Conceptual confusion about electric and magnetic phenomena can occur in students (Guisasola et al., 2004a) and physics instructors (Hekkenberg et al., 2015). A source of confusion about this is interference, the cognitive effect in the learning of a concept when a related concept or task is taught before (proactive) or after (retroactive) (Sayre & Heckler, 2009). The concept of electric and magnetic force can have different interference effects on students' understanding, depending on the moment of instruction (Scaife & Heckler, 2011). After electricity instruction and before covering magnetism, students tend to answer magnetic force questions with electric force answers. After magnetism instruction, the interference reverts; students tend to answer electric force questions with magnetic force answers (Hernandez et al., 2019; Scaife & Heckler, 2011). A study about

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Contribution to the literature

- This is the first study that analyzes interference patterns in students' answers when solving problems that involve Gauss's and Ampere's laws.
- The interference patterns related to the shape of the Gaussian surface or Amperian trajectory and field-related concepts are shared among contexts. The interference related to the source of the field (charge or current) is predominant in magnetism, while that related to using elements from the opposite context in an equation predominates in electricity.
- This study's findings guide introductory and intermediate electricity and magnetism instructors to address this interference phenomenon.

students' understanding of electric and magnetic fields and interactions found a higher tendency to use electricity concepts to answer questions about the magnetic field (Campos et al., 2021; Hernandez et al., 2022). These findings hint that there may be other causes of interference besides the timing of instruction, such as rote learning (or memorization). Other essential electromagnetism topics, such as Gauss's and Ampere's laws, must be studied to understand the causes of interference more deeply.

Several studies have focused on students' conceptual difficulties in understanding Gauss's and Ampere's laws and their related concepts, such as electric flux and magnetic circulation. Among the most prevalent difficulties in both contexts are

(1) confusing the electric field and flux (Guisasola et al., 2003, 2008; Li & Singh, 2018a; Pepper et al., 2012; Singh, 2004, 2006) or the magnetic field and circulation (Bozzo et al., 2022; Guisasola et al., 2003, 2004b, 2008, 2010),

(2) failing to apply the principle of superposition by assuming that only the enclosed field sources create a field (Guisasola et al., 2003, 2004b, 2008; Li & Singh, 2018b; Pepper et al., 2010), and

(3) failing to identify the necessary symmetry conditions to use Gauss's or Ampere's law to calculate the electric or magnetic field (Li & Singh, 2018a, 2018b; Manogue et al., 2006; Pepper et al., 2010, 2012; Singh, 2004, 2006; Traxler et al., 2006; Wallace & Chasteen, 2010).

To our knowledge, the possible interference between electricity and magnetism concepts in using Gauss's and Ampere's laws has not been directly studied in the literature. We aim to explore the interference that may happen when students use elements related to magnetism (such as words or formulas) in their reasoning of Gauss's law and elements of electricity in their reasoning of Ampere's law. This is not a direct study of students' conceptual understanding of Gauss's and Ampere's laws but how interference may be present between these two laws and contexts. As the literature review suggests, this objective is relevant because interference can be a source of conceptual confusion. We present the research questions. Then, we describe the methodological approach, participants, instruments, data collection, and analysis strategy. The results are presented and discussed in four parts: the description of the emerging codes, a comparative analysis for each coding family, a consistency analysis of the interference for each coding family, and implications for teaching. Finally, we conclude with the main takeaways of this article, limitations, and future directions.

RESEARCH QUESTIONS

Based on the literature about interference between electricity and magnetism concepts and our observations while analyzing the data for previous studies (Barniol & Zavala, 2015, Campos et al., 2023; Hernandez et al., 2019, 2021, 2022), we found the opportunity to identify how some elements of magnetism may be present when students reason about Gauss's law, and elements of electricity may be present when students reason about Ampere's law. By the elements of electricity or magnetism, we mean specific words in students' explanations or specific letters in students' written equations that hint at the opposite context (for example, calling the electric field the "magnetic field"). This study analyzes the interference patterns that emerge in students' answers when solving problems involving Gauss's and Ampere's laws.

The research question is: What interference patterns between electricity and magnetism emerge in students when reasoning about Gauss's and Ampere's laws? To answer this question, we consider three specific research questions:

(1) What are the most frequent elements of magnetism present when students reason about Gauss's law?

(2) What are the most frequent elements of electricity present when students reason about Ampere's law?

(3) How consistent is the interference of electricity and magnetism in Gauss's and Ampere's laws among introductory students?

METHODOLOGY

The methodology follows a qualitative research design to identify the interference patterns of electricity and magnetism in students' use of Gauss's and

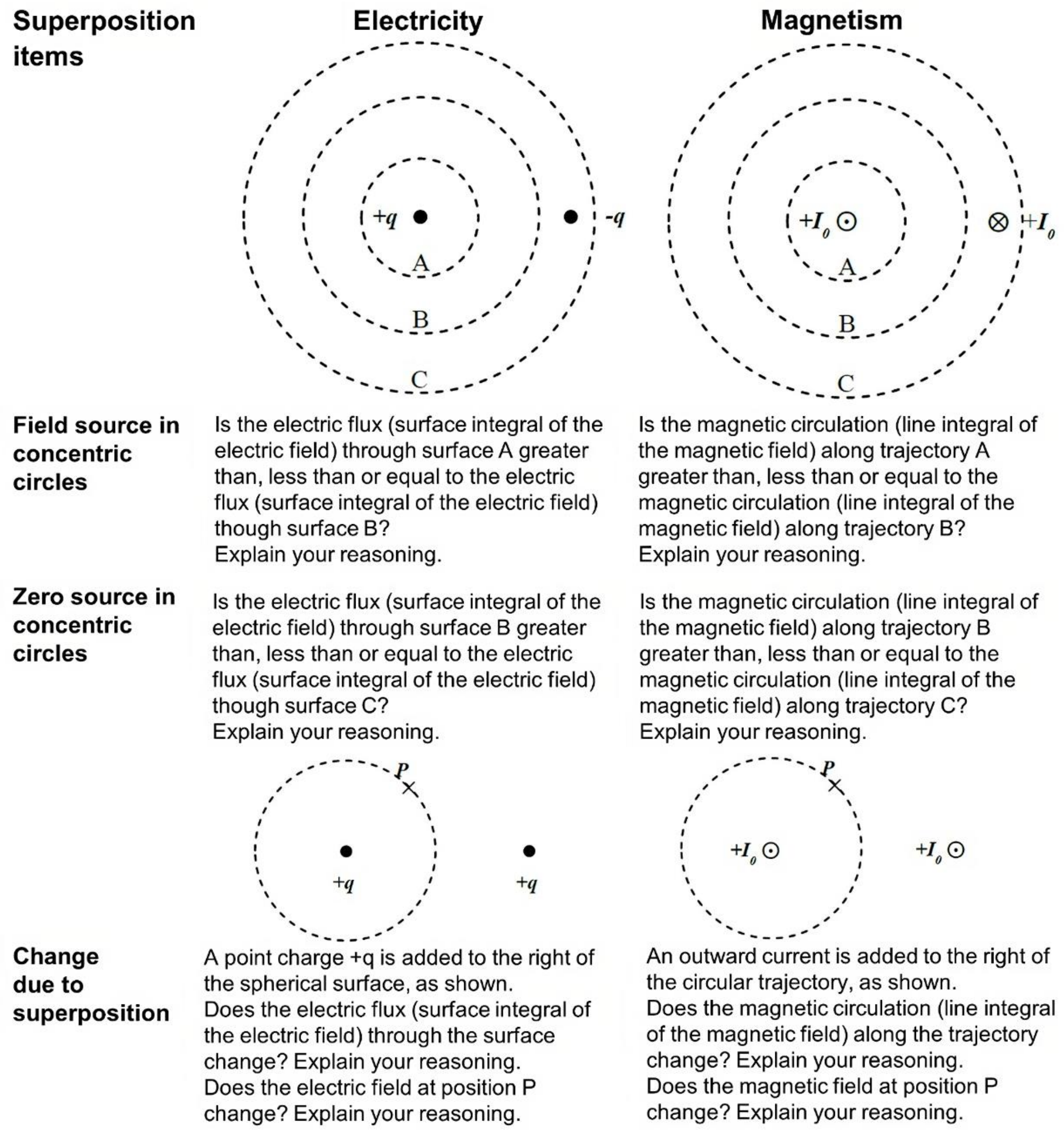

Figure 1. Three parallel items aiming to apply the superposition of Gauss's and Ampere's laws (Source: Authors' own elaboration)

Ampere's laws. The participants were 322 engineering students taking the introductory electricity and magnetism course at a Mexican university. We used two open-ended questionnaires to explore students' understanding and use of Gauss's and Ampere's laws, which underwent literature and expert validation.

The questions explored students' understanding of several topics related to Gauss's and Ampere's laws, such as applying the superposition principle in those laws (superposition items in **Figure 1**), identifying the symmetry conditions to use Gauss's and Ampere's laws to calculate the field (symmetry items in **Figure 2**), and computing (or calculating) the electric flux and magnetic circulation with elemental source distributions (computation items in **Figure 3**).

The questionnaires use parallel representations, a characteristic further exploited in the related publications (Campos et al., 2021, 2023; Hernandez, 2019, 2021, 2022).

Half of the students randomly answered the electricity test (NE=162), and the other half the magnetism test (NM=160). The data analysis focused on identifying whether students presented some element of magnetism when using Gauss's law or of electricity when using Ampere's law. We read through students' responses to identify whether some words of the opposite context were present in each question. We coded the data to specify which elements of electricity (e.g., charge, electric field) and which elements of magnetism (e.g., current, magnetic field) emerged in the students' interference. The coding process did not require interpretation on the authors' side, only identifying if the code was present. This means that when a student wrote "magnetic" instead of "electric," we classified it as an interference (specific examples are found in the results section). We did a tabular classification for each student and question specifying the codes that emerged. When there were no interferences, the corresponding cell was left blank.

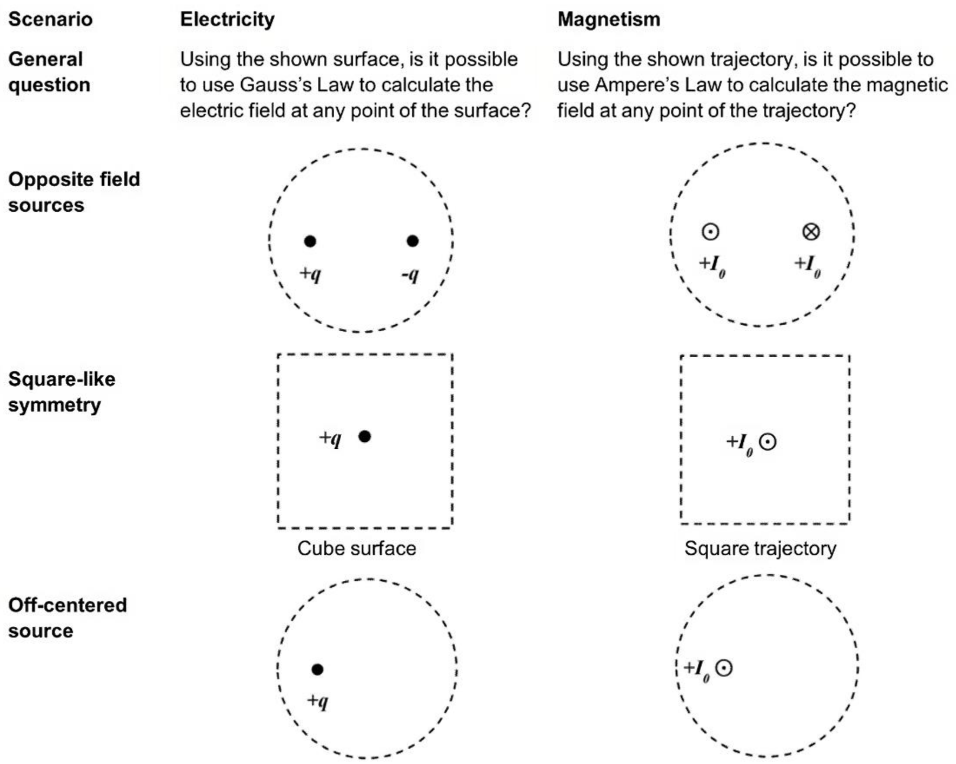

Figure 2. Three parallel items to identify the necessary symmetry for using Gauss's and Ampere's laws to obtain the electric or magnetic field. The same authors presented this figure in a related article (Campos et al., 2023).

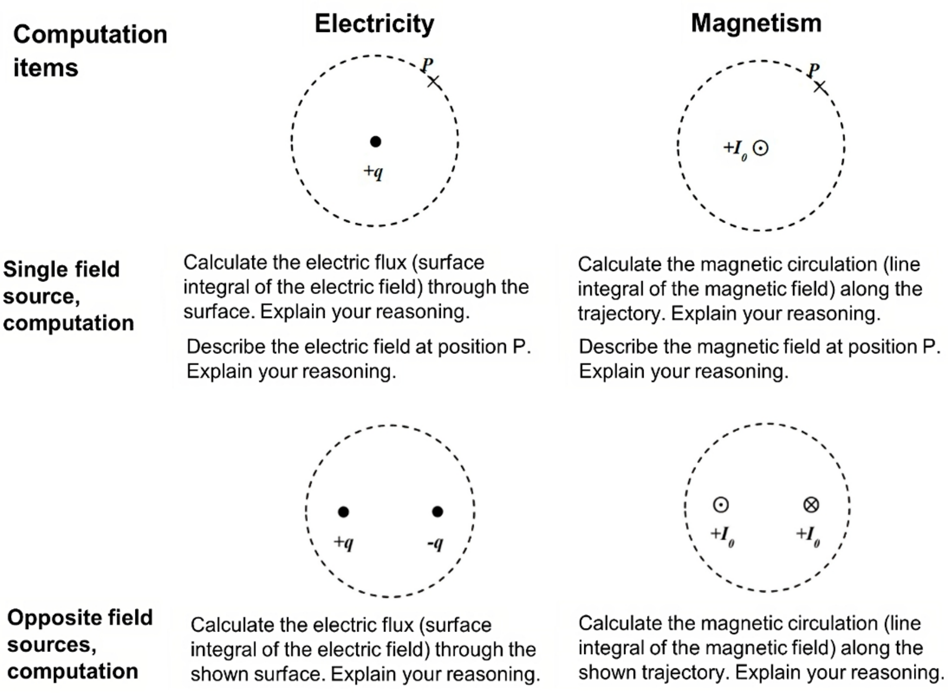

Figure 3. Using Gauss's or Ampere's laws, two parallel items to calculate the electric flux or magnetic circulation (Source: Authors' own elaboration)

RESULTS AND DISCUSSION

The section first presents the codes that emerged from the data with examples. The codes are classified into coding families that group codes with shared characteristics and topics to allow comparison between contexts (e.g., the coding family "shape" involves the codes related to trajectories and surfaces). Afterward, it presents a comparative analysis of the frequency for each family in the different questions. Finally, it presents an analysis of the consistency of interference.

Table 1. Emerging codes and coding families for Ampere's and Gauss's laws

Family	Code	Example
Ampere's law		
Source: Charge	Charge	*"The **charges** are at the same distance from the trajectories."*
Shape: Surface	Area	*"It is only I_0 inside the enclosed **area.**"*
	Surface	*"Because it is an Amperian **surface.**"*
	Sphere	*"It is the same inside the **sphere.**"*
Field concept	Flux	*"The magnetic **flux** outside a conductor is zero."*
	Gauss	*"Because it uses a **Gaussian** figure and detects field through that trajectory."*
	Electric field	*"The sum of **electric field** reduces the magnitude of the other force."*
	Positive current	*"They repel each other because they are both **positive.**"*
	Lenz's law	*"Using **Lenz's law**, it is possible to calculate the magnetic circulation."*
		Gauss's law
Source: Current	Current	*"Flux in B is greater than in A because it has more area that allows the **current** to flow."*
Shape: Trajectory	Differential dl	*"Because the **differential dl** has a smaller distance."*
	Trajectory (loop)	*"Yes, because the equation is not exclusively for circular **loops**."*
	Circle/square	*"No, the distance from the **square** to the point varies."*
Field concept	Magnetic flux	*"The electric flux does not change because the **magnetic flux** inside the surface is the same."*
	Ampere	*"It is outside the **Amperian** surface, so it does not count."*
	Magnetic field	*"The **magnetic field** would only change due to the area that encloses it."*
	Tangential	*"It would be **tangent** to the circle."*
	Lorentz's force	"$F = qv \times B$"
Equation	Equation with B	"$\oint B \cdot dA$"
	Equation with Miu	"$\mu_0 q_{enc} = (\mu_0)(+q)$"
	Equation with a cross product	"$E \times dA$"

Emerging Codes

The codes emerged from the data as a first approach to data analysis. We obtained nine codes of electric interference in Ampere's law questions and 12 codes of magnetic interference in Gauss's law questions. We comparatively analyzed all the codes and frequencies and classified them into coding families. For example, the codes "surface," "area," and "sphere" were classified into the coding family "shape" because they all refer to a characteristic of the shape.

Table 1 compares the emerging families, their corresponding codes, and an example for each code. The codes emerged only by observing a specific word or element in an equation, regardless of the students' conceptualization. In other words, we focused on whether a word or element in an equation denoted interference. We did not try to link this interference to a specific difficulty in conceptual understanding. This process was performed by two of the authors and compared. In the case of disagreement, they were reviewed by all the authors. The parallel codes in both contexts allowed for triangulation between the two instruments. In other studies (Campos et al., 2023; Hernandez et al., 2021), we focused on conceptual difficulties rather than the appearance of interference; the former requires a profound interpretation of students' answers. In this case, there is no interpretation from the researcher's perspective, only observation of whether the interfering word or element in an equation is present.

The most relevant coding families in both contexts refer to the electric or magnetic field source, the shape (surface or trajectory), the confusion with other concepts related to the electric or magnetic field, and the use of equations. We found a similar but not identical structure in the literature. A previous study reported the electricity elements present in the questions of magnetism, focusing on the source of the field and the use of field lines. In other words, it reported that students referred to charged poles in magnetism and Ampere's laws questions and referred to this category as "electricity" and the use of the field line representation (Guisasola et al., 2004a). We can find a similarity between the "electricity" category in their study and our "source" coding family and a slight similarity between the "field lines" category and our "field concept" coding family. However, the "shape" and "equation" coding families emerged in our data as possible sources of interference that had not been reported in the literature.

Comparative Analysis

The comparative analysis presents the frequency of total interference for each item and the frequency for each coding family in the two contexts. **Figure 4** provides an overview of the results, and **Table 2** presents the analysis of the total interference for each item, classified according to the item's objective. **Figure 4** shows that the equation family is relevant in the electricity context and the source family in the magnetism context.

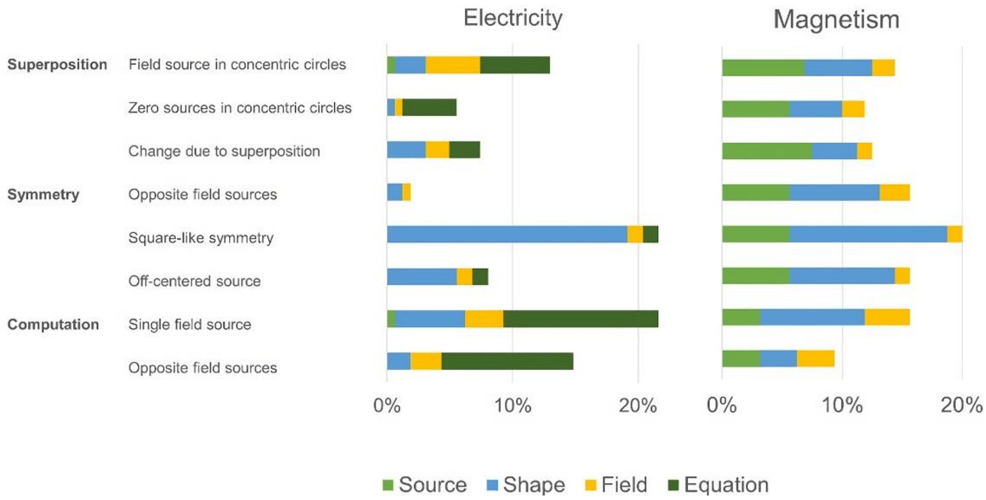

Figure 4. Overview of interference coding families in each context. The source family is more relevant in magnetism, and equation family, in electricity, and the shape and field families present similar behaviors (Source: Authors' own elaboration)

Table 2. Comparison of frequency of total interference found in each item. Percentage refers to students who presented an interference element, regardless of coding family. Items are organized depending on their objective: superposition, symmetry, or computation

Objective	Item	Gauss	Ampere
Superposition	Field source in concentric circles	13%	14%
	Zero sources in concentric circles	6%	12%
	Change due to superposition	7%	13%
Symmetry	Opposite field sources	2%	16%
	Square-like symmetry	22%	20%
	Off-centered source	8%	16%
Computation	Single field source	22%	16%
	Opposite field sources	15%	9%

The other two families, shape and field, have similar behaviors that can be analyzed in more detail. As seen, four of eight items of Gauss's law and seven of eight items in the context of Ampere's law exceed 10% of the students.

In **Table 2**, we can see that the interference is more relevant in the context of Ampere's law in the items with a superposition objective and the identification of symmetry. In contrast, the items with a computation objective are more relevant in Gauss's law. These frequencies evidence the relevance of analyzing the interference patterns for each coding family in the subsequent sections.

The results imply that the interference of electricity elements when using Ampere's law is more frequent than that of magnetism when using Gauss's law. This finding is in line with(Campos et al., 2021; Hernandez et al., 2022), where it has been found that the time of instruction is not the only possible cause for interference. The analysis of the coding families would shed light on other possible causes for interference.

Table 3. Comparison of frequency for coding family "source." This family includes "current" code when using Gauss's law and "charge" code when using Ampere's law. Items are organized according to superposition, symmetry, and computation objectives

Context	Gauss	Ampere
Item	Current	Charge
Field source in concentric circles	0.6%	6.9%
Zero sources in concentric circles	0.0%	5.6%
Change due to superposition	0.0%	7.5%
Opposite field sources, symmetry	0.0%	5.6%
Square-like symmetry	0.0%	5.6%
Off-centered source	0.0%	5.6%
Single field source, computation	0.6%	3.1%
Opposite field sources, computation	0.0%	3.1%

Coding family: Source

Table 3 compares the "source" coding family, which includes the "charge" code when using Ampere's law and the "current" code when using Gauss's law.

As seen, the "charge" code was the most relevant cause of interference in the context of Ampere's law, while the "current" code was almost non-existing in the context of Gauss's law. Moreover, more than 5% of students referred to currents as charges in the items aiming to apply the superposition principle. The same pattern emerges in the items that evaluate the use of symmetry for applying Ampere's law. In the two items that require a calculation, the impact of this category is reduced to 3%, indicating that students are more likely to realize that the source field is an electric current when using an equation. The emergence and frequency of this code indicate that, after instruction, students may carry naïve conceptions, such as that static electric charges produce a magnetic field, in line with known conception of charged poles (Maloney, 1985). This result adds to discussion prompted by Maloney (1985), hinting that the idea of charged poles stems from a mixed outcome of students' initial conceptions and what they were taught.

Table 4. Comparison of frequency for coding family "shape." This family includes "trajectory" code when using Gauss's law and "current" code when using Ampere's law. Items are organized according to superposition, symmetry, and computation objectives

Context	Gauss	Ampere
Item	Trajectory	Surface
Field source in concentric circles	2.5%	5.6%
Zero sources in concentric circles	0.6%	4.4%
Change due to superposition	3.0%	3.8%
Opposite field sources, symmetry	1.2%	7.5%
Square-like symmetry	19.1%	13.1%
Off-centered source	5.6%	8.8%
Single field source, computation	5.6%	8.8%
Opposite field sources, computation	1.9%	3.1%

Table 5. Comparison of frequency for coding family "field concept." In context of Gauss's law, this includes elements related to magnetic field. In context of Ampere's law, this includes elements related to electric field. Items are organized according to superposition, symmetry, and computation objectives

Context	Gauss	Ampere
Field source in concentric circles	4.3%	1.9%
Zero sources in concentric circles	0.6%	1.9%
Change due to superposition	1.9%	1.3%
Opposite field sources, symmetry	0.6%	2.5%
Square-like symmetry	1.2%	1.3%
Off-centered source	1.2%	1.3%
Single field source, computation	3.1%	3.8%
Opposite field sources, computation	2.5%	3.1%

We believe that students' preconceived ideas of electric charge remain in their minds and combine with the new concepts they learn in the introductory electricity and magnetism course, specifically in applying Ampere's law. We consider that this interference is proactive (Sayre & Heckler, 2009) in the sense that a concept that was taught previously (or even a misconception that was developed earlier) interferes with using Ampere's law.

Coding family: Shape

Table 4 compares the "shape" coding family, which includes the codes related to trajectories when using Gauss's law and those related to surfaces when using Ampere's law. The shape family was more relevant in the context of Ampere's law than in Gauss's law in most items, which could indicate that this interference is proactive (when a related concept or task is taught before) (Sayre & Heckler, 2009). In the item "square-like symmetry," the shape family the most relevant source of interference in both contexts. It is relevant to notice that, in a previous study, it was found that surface features play an essential role in how students interpret and answer this item because it explores a different surface or trajectory than what is traditionally studied in the electricity and magnetism course (Hernandez et al., 2021). When analyzing the interference of magnetism elements in the use of Gauss's law, any student who would mention a square rather than a cube or circle rather than a sphere (e.g., "it is a square" or "it is not a circle"), was considered an interference because Amperian trajectories are two-dimensional while Gaussian surfaces are three-dimensional. However, we acknowledge that the representation may substantially affect this item because the cubic surface was represented with a square, even if it had the text "cubic surface" underneath. In the case of Ampere's law, the interference of electricity elements refers mainly to students calling the shape an area or a surface rather than a trajectory or loop. So, the source of interference for both contexts is different in this item. The interference in Ampere's law may stem from confusing trajectories and surfaces, while the interference in Gauss's law may be due to the surface features of this specific item.

Coding family: Field concept

Table 5 compares the "field concept" coding family, which includes the codes related to the magnetic field when using Gauss's law and those related to the electric field when using Ampere's law. The family is broader than just the electric or magnetic field concept; all the elements are somehow related. In the context of Ampere's law, this interference includes students who referred to the electric field, the concept of flux, Gauss's law, that the current was positive (instead of outward), and Lenz's law. In the context of Gauss's law, this interference includes students referring to the magnetic field, magnetic flux, Ampere's law, or tangent direction. In this comparison, there was not a clear pattern of interference in any of the two contexts, and the frequencies were relatively small. It is noteworthy to analyze the item "field source in concentric circles," where this source of interference is deemed relevant in the context of Gauss's law (around 5%). In this case, the main code was students referring to the magnetic field, which could reinforce the previously mentioned association of electric charge and magnetic field and the mixed concepts introduced by Maloney (1985). However, given the minor frequency in the rest of the items in the two contexts, there was not enough evidence in this data to reach a solid conclusion.

Coding family: Equation

Table 6 shows coding family "equation" results, which only emerged in the context of Gauss's law. This coding family includes students who used elements of magnetism in an equation for Gauss's law, mainly by writing B (magnetic field), and in some cases μ, or a cross product. This interference is retroactive (when a related concept or task is taught after) (Sayre & Heckler, 2009) because a recently acquired knowledge (of magnetism)

Table 6. Frequency for coding family "equation" in context of Gauss's law, and coding family did not emerge in context of Ampere's law. Items are organized according to superposition, symmetry, and computation objectives

Context	Gauss	Ampere
Field source in concentric circles	5.6%	0%
Zero sources in concentric circles	4.3%	0%
Change due to superposition	2.5%	0%
Opposite field sources, symmetry	0.0%	0%
Square-like symmetry	1.2%	0%
Off-centered source	1.2%	0%
Single field source, computation	12.4%	0%
Opposite field sources, computation	10.5%	0%

interferes with Gauss's law equation. Due to the nature of the questions, it was natural that this code was not very relevant to the items of symmetry identification. However, it was relevant in the items of superposition (between 3% and 5%) and the most relevant coding family in the items that require computation of the electric flux (more than 10%). This analysis provides solid evidence for the previously introduced discussion of the association between electric charge and magnetic field (Maloney, 1985). When students express their ideas in an equation, either to apply superposition or to calculate a quantity, they tend to think of a magnetic field, causing interference in applying Gauss's law.

Students may be more comfortable with the concept of the magnetic field due to their previous experience with magnets in high school or non-formal contexts. Before their university studies, many students become familiar mainly with magnets and charges through popular culture (their personal experience with magnets on the refrigerator, references in movies, songs, or TV shows, etc.) without fully understanding them or seeing them as separate phenomena.

Consistency Analysis

We present a consistency analysis to quantify the times each student presents an interfering element. This consistency analysis is partially based on previous studies, where we analyzed how students responded to questions by repeating their reasoning (Campos et al., 2019; Hernandez et al., 2022). To perform the consistency analysis, we counted the number of interferences that each student presented. The maximum possible was eight interferences (if they presented interference in every question), and the minimum possible was 0 interferences (if they did not present interference in any question).

Figure 5 presents the distribution of interference in general. In the context of Gauss's law, we found that 56% of students did not present any interference, which means that 44% presented at least one interference. Only one student presented six interferences; no students presented seven or eight. The mean interference is $\mu_G=1.15$, with a standard deviation of $\sigma_G=1.51$. In the context of Ampere's law, 53% of students presented at least one interference. In this case, three students presented six interferences, one student had seven interferences, and no students had eight. The mean interference is $\mu_A=0.93$, with standard deviation $\sigma_A=1.36$. The difference between the distributions is not statistically significant (p-value=0.091).

Figure 6 presents the consistency analysis for each coding family. The coding families source and equation present contrasting behaviors. In the source coding family, only 1% of students presented this interference at least once in electricity, compared to 25% in magnetism. Of the 25% in the magnetism context, 13% presented it only once, 8% twice, and 5% three or more times. In the equation coding family, 20% of students presented this interference in electricity, and no students in magnetism.

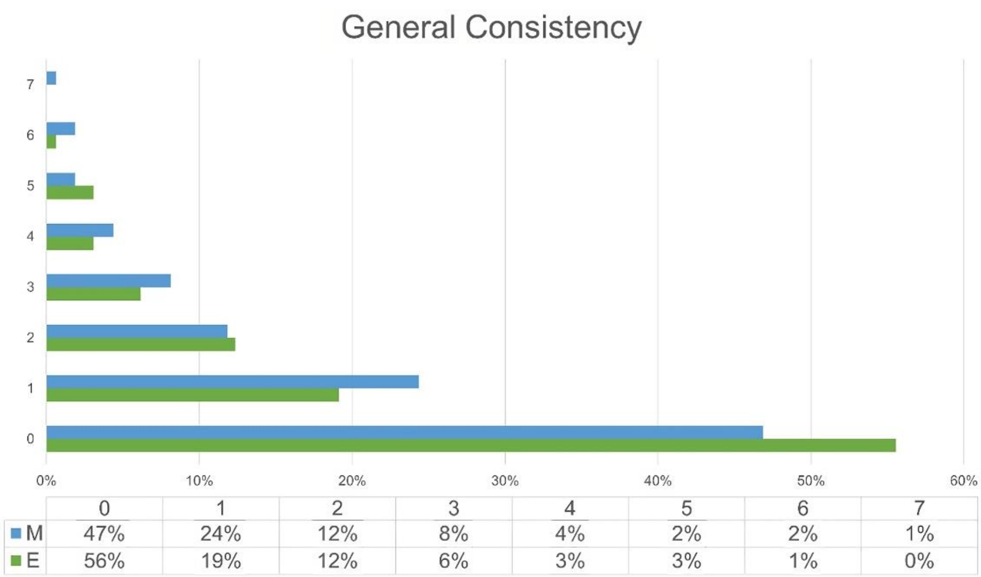

Figure 5. Distribution pattern of consistency of interference between Gauss's and Ampere's laws (Source: Authors' own elaboration)

Figure 6. Distribution pattern of consistency of interference between Gauss's and Ampere's laws for each coding family. Source family accounts for 25% of students in magnetism context. Shape family has 24% of students in electricity and 30% in magnetism. Field family has around 10% of students in both contexts. Equation family is relevant only in magnetism context with 20% of students (Source: Authors' own elaboration)

Of the 20% in the electricity context, 9% presented it once, 6% twice, and 6% three or more times. Compared to the other charts, the behavior of these coding families follows the same pattern as the general consistency in the opposite contexts. In other words, the equation interference was relevant in the electricity context and the source interference in the magnetism context. The consistency of the shape and field interferences has the same pattern in both contexts. "Shape" has a similar behavior as the general consistency; 24% presented this interference at least once in electricity and 30% in magnetism. In the case of a field, the consistency is less prevalent (around 10% of students presented this interference in both contexts).

Overview of the Findings

The main research findings were that, when analyzing the emerging codes in the two contexts, we observed that the interference patterns related to the shape of the Gaussian surface or Amperian trajectory and field-related concepts are shared among contexts. When analyzing each coding family individually, it was evident that the interference patterns related to the source of the field are more frequent in the magnetism context. This means that students would more often write "charge" instead of "current" when answering an Ampere's law question. In the electricity context, the interference patterns are more frequently related to using elements from magnetism in an equation, for example, writing Gauss's law as the dot product between B (magnetic field) and the differential of area. These findings can guide introductory and intermediate electricity and magnetism instructors to address this interference phenomenon, as the following section shares.

Implications for Teaching

The interference analysis between Gauss's and Ampere's laws can help introductory electricity and magnetism instructors know the interference effect when teaching these concepts. Instructors should reflect on how Gauss's and Ampere's laws are presented in class and the time dedicated to understanding the concepts of electric flux and magnetic circulation and their relations to the electric and magnetic fields, respectively. We encourage electricity and magnetism instructors to design active learning activities that include cognitive scaffolding (Zavala, 2019) or tutorials (Barniol & Zavala, 2015, 2016) to address the possible interference explicitly.

When teaching the sources of field, instructors should make explicit that electric charges create electric fields, and electric currents (or electric charges in motion) create magnetic fields. It is also important to explicitly address the interference of charged poles. The following thought may seem contradictory to students: Why are magnetic poles not charged if electric charges in motion create magnetic fields? To this aim, instruction should cover the effects of electric and magnetic fields on materials, especially the differentiation of ferromagnetic, paramagnetic, and diamagnetic materials. Also, emphasize what it means to charge something (excess vs. zero net charge). Instructors could prompt this kind of discussion among students and ask them to explain how the magnetic field affects each type of material on a microscopic scale and analyze the net charge after magnetization. This kind of discussion should be done when introducing the concepts of charge and field. However, the evidence of this study suggests that the interference of electricity concepts in Ampere's law could be reduced by addressing the confusion of charged poles.

We recommend explicitly differentiating their properties to reduce the possible interference caused by the shapes of Gaussian surfaces and Amperian trajectories. After Gauss's law instruction, students have learned about Gaussian surfaces and surface integrals. They have become familiar with the two-dimensional representations of three-dimensional space. When introducing Ampere's law with its parallel representations, students can confuse the trajectories with surfaces, mainly because both circular trajectories and spherical surfaces are usually represented with a circle. Instructors could address this interference by prompting students to distinguish between a trajectory and a surface. One example would be considering the different surfaces related to a specific trajectory (Griffiths, 2017), such as in (Boyer, 2019). In their example, the authors used several surfaces related to an Amperian trajectory to illustrate Maxwell's displacement term in Ampere's laws. We are not proposing such an advanced treatment in introductory physics courses; however, prompting students to think of the different surfaces related to a trajectory can help them differentiate between the two terms when applying Ampere's law and prompt a discussion of how a closed trajectory is intrinsically related to open rather than closed surfaces.

When teaching Ampere's law, instructors must dedicate time and practice to understanding the concept of magnetic circulation, just as it is usually done for the electric flux when teaching Gauss's law. Explicitly identifying the equations of magnetic flux and contrasting them with electric flux could also help reduce the interference of magnetism elements in the equations of Gauss's law.

CONCLUSIONS

This article analyzed the interference patterns of electricity and magnetism elements that emerged in students' answers when solving problems that involve Gauss's and Ampere's laws. The study had a qualitative research design involving open-ended questionnaires with eight items about Gauss's and Ampere's laws regarding the superposition principle, the symmetry necessary to calculate the field, and calculating the electric flux or magnetic circulation of elemental charge distributions. The students' answers were analyzed based on emerging codes and coding families, with examples and frequency for each coding family. Additionally, the consistency of students' interference was analyzed and compared between contexts. The study's main finding is that the electricity elements in students' answers to Ampere's laws problems differ from the magnetism elements in students' answers to Gauss's law problems. The most frequent electricity element in Ampere's law referred to the source of the field as an electric charge, while the most frequent magnetism element in Gauss's law included the magnetic field in the equation.

The study has limitations regarding the depth and generalizability of the results. The choice of an open-ended questionnaire provided the basis for exploration. However, it would be necessary to conduct interviews to get an in-depth overview of the sources of interference. It would also be valuable to broaden the scope of the analysis through quantitative instruments, such as multiple-choice questions that include an interfering element between electricity and magnetism concepts. The interference between electricity and magnetism contexts can be further studied in other topics besides Gauss's and Ampere's laws. Electromagnetism has a wide range of similar topics, such as sources of field, fields, interactions, and the superposition principle, to name a few. Finally, it is necessary to conduct research that links the interference between contexts with students' conceptual understanding of the topics.

This article contributes a systematic and comparative analysis of interference between electricity and magnetism when solving problems involving Gauss's and Ampere's laws. This study's findings can benefit instruction in introductory electromagnetism courses at the university level. One of our recommendations for instruction is to address the possible sources of interference explicitly and dedicate time and practice to understanding electric flux and magnetic circulation with active learning strategies. Most importantly, the findings point to students' preconceptions about charges and magnetism that stem from their everyday life through experience, popular culture, or oversimplified treatment of these concepts in early education. These preconceptions seem to persist in university, affecting the interference patterns found in this study. We recommend performing more research and proposing educational interventions at pre-university levels, like middle and high school, to prevent the interference between electricity and magnetism concepts at university.

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