Engineering Professors' Conceptions on the Conceptual Field of Electrostatics in Mexico

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Abstract

This study explores the conceptual understanding of electromagnetism among physics professors at the Aeronautical University in Querétaro, Mexico. While student misconceptions in electromagnetism have been extensively studied, research on professors' understanding and its potential impact remains limited. This research aims to address this gap by focusing on the core concepts of electrostatic force, electric field, and electric potential.

Eight professors participated in the study. Their academic background, electromagnetism course history, and teaching experience were documented. A three-tier diagnostic test, based on Vergnaud's theory of conceptual fields, was then used to assess their conceptualisation of these concepts and their interrelationships.

The analysis revealed that only one professor consistently demonstrated correct understanding across all three concepts. Interestingly, this professor was also the one with the most extensive teaching experience in the subject. The results suggest a potential connection between teaching experience and a deeper conceptual understanding of electromagnetism. Further research is needed to explore this connection and its implications for mitigating student misconceptions through effective teaching practices.

Introduction

Correct and well-established concepts are the building blocks from which knowledge is constructed in every scientific discipline. Therefore, it is important to have a solid comprehension of the concepts if we want basic knowledge to be developed and to be applied in problem-solving (Liu & Fang, 2016). However, it is common to find problems in the construction of knowledge because these building blocks are "weak" and can't be used as a solid base to generate a cognitive structure about a specific concept, especially in science concepts (Özmen, 2004). Therefore, it is important to identify which concepts are difficult for students to learn so that adjustments can be made in the process, to improve the teaching and learning of these concepts and to prevent them from hindering knowledge construction and potentially causing students to develop misconceptions. This highlights the need to address the origin of students' misconceptions, as they can act as obstacles to building a solid foundation in science concepts.

The issue of "weak" concepts extends beyond students and can also affect teachers, hindering their ability to effectively guide students' knowledge construction. Physics Education Research

(PER) has extensively explored student misconceptions; however, given the crucial role teachers play in students' learning, understanding their conceptual grasp is equally important. Surprisingly, few studies address the misconceptions teachers might possess (López-Garduza et al., 2022). Many physics teachers may have misconceptions, which can directly hinder students' understanding of key concepts and ideas. After all, meaningful learning of scientific concepts depends upon the teacher-student communication process (Karakuyu & Tüysüz, 2011), which emphasises the importance of ensuring that whatever the teacher communicates to their students has a proper conceptual foundation. For every student, this will form a starting point to shape their previous experiences into knowledge about the concepts addressed in the classroom (Driver, 1989; Driver et al., 1994). While different studies have established a strong connection between science teachers' competence and their content knowledge (Verdugo et al., 2016), the lack of research on teacher misconceptions presents a significant gap in our understanding of how misconceptions arise and potentially influence students.

Research on students' misconceptions of electromagnetism demonstrates that only between 30% and 40% of students correctly answer questions about electrostatics (Smaill & Rowe, 2012; Hashish et al., 2020). This is concerning, and it is likely that teachers' results are similar to those obtained by students and even as widely shared as students' misconceptions (Johnston & Miller, 2000). Unfortunately, there is not much information about teachers' misconceptions, especially on the subject of electricity and magnetism. Between the little research conducted regarding teachers' misconceptions in this subject, there are studies on the concepts of electric charges and their properties (Doğru, 2021; Stefanidou et al., 2019), electric fields (Türkkan, 2017), and electric currents (Sert Çıbık, 2017) but none of these aim to identify the conceptualisation made by in-service teachers. It is also evident that most of the studies in electricity and magnetism have focused on topics related to charge properties, electric currents, and DC circuits, neglecting the core concepts of the subject.

In electricity and magnetism, the concepts of electrostatic force, electric fields, electric potential, and the relationships between them, are the basic concepts that serve as building blocks for electrostatics. These concepts are very well tied together, forming a set that must be analysed as a whole system so that it can be understood, which Vergnaud (2009) calls a Conceptual Field.

According to Vergnaud's Conceptual Field Theory (CFT), language is composed of a set of conceptual fields, which are organised around a central concept or prototype. These fields are interconnected and overlap, creating a network of meaning. Conceptual field theory is a framework used in physics to understand the relationships between different physical concepts and the ways in which they interact. CFT emphasises the relationships between different physical concepts, contrasting with the traditional approach in physics, which tends to view physical concepts as separate and distinct entities. Another important aspect of conceptual field theory is the idea that physical concepts are not static, but rather constantly changing and evolving. This means that the fields representing these concepts are also constantly changing and that the relationships between them are always in flux. One of the potential contributions of CFT to physics education research is the identification of misconceptions and the design of instructional strategies to address these misconceptions.

A case study is presented, on the first stage of the process of characterising the conceptualisation of a group of eight teachers on the conceptual field of electrostatics in the Aeronautical University in Queretaro (Mexico). Given the small number of teachers involved in this stage of the study and its qualitative nature, generalisations won't be made. Only a general description of the current situation of this group of teachers is presented.

This article presents the results of the first stage of the process of characterising the conceptualisation of a group of eight professors from the Aeronautical University in Queretaro (Mexico) on the conceptual field of electrostatics.

First, the academic background of each professor is described, including the number of electromagnetism courses they have taken during their formal education, the number of professional development courses they have taken in the subject, and their experience teaching the subject of electricity and magnetism.

Then, the design of a three-tier diagnostic test to assess the conceptualisation of the conceptual field of electrostatics (electrostatic force, electric field, and electric potential), is described. Intervals are proposed to establish whether a professor correctly conceptualises a concept, has misconceptions, or has no knowledge of it. Based on the results for each concept, it is established whether or not the conceptual field of electrostatics is correctly conceptualised.

Finally, results for each professor are described, in relation to some particularities of their academic background and teaching experience.

Methods

The scope of this study is limited to describing the results of in-service physics teachers at the Aeronautical University in Querétaro, obtained in a diagnostic test designed to identify if the professors have misconceptions on the conceptual field of electrostatics.

The stages of this study were:

- Design and validation of the diagnostic test to identify what teachers conceptualise about the conceptual field of electrostatics.
- Characterisation of the group of teachers involved in the study. Information was collected on undergraduate and graduate education, professional development and experience teaching electricity and magnetism.
- Application of the diagnostic test.
- Analysis and characterisation of teachers' conceptualisation about the conceptual field of electrostatics.
- Discussion about teachers' results and their relation to their academic formation and teaching experience.

Diagnostic Test

A three-tier diagnostic test was designed to identify teachers' misconceptions regarding the electrostatic force, electric field, and electric potential. There is an emerging trend in science education to develop multi-tier tests in order to obtain more information about students' and teachers' understanding (Gurel et al., 2015; Kamcharean & Wattanakasiwich, 2016). The first tier includes multiple-choice content questions, and the second tier includes a multiple-choice set of reasons for the answer to the first tier. The third tier is an open question where teachers were asked to explain or justify their answers to the first and second tiers. If they didn't think a good justification was provided between the options for the second tier, they could propose a different one.

This diagnostic test went through content validation by expert judgement before being applied to the participants in this study. Three different physics education researchers were consulted and asked to validate the questions in the test, to make sure that every item was understandable and relevant to the objective pursued in the study.

The diagnostic test consists of sixteen 3-tier questions (48 items in total) where most of the questions assess knowledge on two or three of the concepts at the same time, due to the intimate relation between the concepts and according to Vergnaud's CFT.

Every item assesses different attributes of each concept. Unlike other instruments where every single item is used to decide whether there are misconceptions on different concepts, this instrument uses an average on the different attributes measured with each item, to decide if each concept (electrostatic force, electric field, and electric potential) is correctly conceptualised.

It's important to note that only three of the questions require a general knowledge on some concepts of vector calculus. Essentially, it is required that the professors know that the work done by the electric field between two points is independent of the path and that the field can be obtained as the gradient of the potential function.

Table 1 presents the questions used to assess every concept and the relation between them in the diagnostic test.

Table 1. Concepts assessed per question.

CONCEPTS		QUESTIONS	NUMBER OF QUESTIONS
$\vec{F}$	Electrostatic Force	1 – 5	5
$\vec{F}-\vec{E}$	Electrostatic Force – Electric Field	6, 9 – 11	4
$\vec{E}$	Electric Field	7, 8	2
$\vec{E}-V$	Electric Field – Electric Potential	12 – 15	4
$\vec{F}-\vec{E}-V$	Force – Field – Potential	16	1

Validation of Correct Answers and Definition of a Correct Attribute of a Concept

Teachers' answers were initially considered correct when both the correct choice and justification were given (first and second tier). However, the answer to the third tier is essential to decide whether an attribute of the concept is correct or not.

In Table 2, an example of the answers to question 16 which assesses one attribute of the concepts of electrostatic force, electric field, and electric potential, is presented. The eight professors are labelled in the second row of the table, and their results for each item of the question are presented as a column below their label. A fictional ninth professor was added to exemplify and describe one of the possible combinations of answers provided by professors.

Table 2. Example of answers to a specific attribute of the concepts of electrostatic force, electric field, and electric potential.

$\vec{F} - \vec{E} - V$ - Question 16									
Professor	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1st Tier	✓	✗	✓	✓	✗	✓	✗	✓	✗
2nd Tier	✗	✗	✓	✓	✗	✓	✗	✓	✓
3rd Tier	✓	✗	✓	✓	✗	✓	✗	✗	✓
Correct Attribute	✓	✗	✓	✓	✗	✓	✗	✗	✓

The following are the descriptions of the possible combinations of responses for the three tiers and the way they were analysed to determine if the question was considered correct or not.

Case 1

When both the first and second tiers are correct, it is expected that the third tier will also be correct since the professors were asked to write a complement to the justification selected in the second tier, or even a correction if they thought there was a mistake in the answer options for both first and second tier. Professor 6 in Table 2 exemplifies this case, where both tiers are correct and the third tier complements or corrects, leading to a correct attribute assessment.

Case 2

If the answer to the second tier was incorrect, but a correct explanation was given in the third tier, the answer to the whole question was considered to be correct. Otherwise, the question is confirmed as incorrect.

It is important to remark that the authors of this study do not make any subjective decision when referring to a correct explanation in the third tier. An explanation given in the third tier is considered to be correct if it is in agreement with the correct justification provided in the second tier. For all the questions in the diagnostic test, one of the answer options for the justification (second tier) was: "The correct justification was not provided between the options. Elaborate your own justification in the next item". When this justification provided by the professor in their own words matched the correct one provided in the second tier, then the attribute was marked as understood.

In Table 2, professor 1 is an example of this case. He didn't select the correct justification provided in the second tier, but his answer to the third tier agrees with the correct justification.

Case 3

If both the first and second tiers were correct, but the explanation provided in the third tier contradicted any of the previous items, the answer was also considered to be incorrect. The answers provided by Professor 8 are an example of this case (see Table 2).

Case 4

The last case was when the answer to the first tier was incorrect but the justification in the second tier was correct and the answer to the third tier corrected the wrong answer selected in the first item. The answer of the fictional Professor 9, presented in Table 2, is an example of this case.

Teacher Characterisation

The characterisation for the group of teachers (see Table 3) shows that 50% have an undergraduate degree in physics (4 teachers), and only 37.5% (3 teachers) have a graduate degree in physics. It is not uncommon in Mexican universities to have teachers with an engineering background teaching math and physics courses.

All eight professors have a Master's degree. Professor 4 has a Master's degree in mathematics, and that is the reason why it is not reported in Table 3.

Table 3. General information of the group of teachers. D1 degree refers to a bachelor's degree, D2 refers to a master's degree and D3 refers to a PhD.

Professor	Physics Degrees			Engineering Degrees			Electromagnetism Courses Taken		Electricity and Magnetism Courses Taught
	D1	D2	D3	D1	D2	D3	Formal Education	Professional Development	
1				✓	✓		1	1	0
2	✓	✓	✓				5	0	1
3	✓	✓					3	0	5
4	✓						1	0	0
5	✓	✓					3	0	3
6				✓	✓		1	0	20
7				✓	✓	✓	2	1	3
8				✓	✓		0	0	6

It is worth noting the following data:

- 4 professors have an undergraduate physics degree and 4 professors have an undergraduate engineering degree.
- Professor 2 is the only professor with a PhD degree in physics.
- All 4 professors with an undergraduate engineering degree have a master's degree in engineering and one of them also has a PhD degree.
- By the time this study took place, professors 1 and 4 had never taught an electricity and magnetism course.
- Professor 6 does not have an undergraduate education in physics but has taught the electricity and magnetism course 20 times.
- Professor 2 has a PhD degree in physics and has taken 5 different electricity and magnetism courses during his undergraduate and graduate education.
- Professor 6 has not taken professional development courses related to the subject during the last three years, but he took a training course in electromagnetism in 2015 before he taught his first electricity and magnetism course at the university.

Misconception Analysis

The total number of questions of the diagnostic test used to assess every concept is presented in Table 4.

Table 4. Total number of questions per concept assessed in the diagnostic test.

CONCEPT		NUMBER OF QUESTIONS
$\vec{F}$	Electrostatic Force	10
$\vec{E}$	Electric Field	11
V	Electric Potential	5

For the purpose of this study, we defined 80% of answers correct as the criterion to consider one concept as understood. This percentage implies that for the electric force concept, only two mistakes are allowed, at most. For the concept of electric field, 3 mistakes are possible and for the concept of electric potential only one. To consider that there is a lack of knowledge about the concept, we chose a definition of less than 50% of answers correct. These intervals are shown in Table 5.

Table 5. Conceptualisation categories according to the understanding of the concept attributes.

Conceptualisation Categories	Percentage of Correct Answers
Lack of Knowledge	$\leq 50\ \%$
Misconception	$(50\% - 80\%)$
Correct conceptualisation	$\geq 80\ \%$

These intervals and categories are an original proposal, based on the different attributes measured in each concept and have also been validated by another three professors and researchers. However, these intervals are consistent with the misconception levels reported in studies focused on students (Mustari et al., 2020; Yamtinah et al., 2019; Irfandi et al., 2022) and future teachers (Pasaribu et al., 2023).

The criterion of 80% for correct conceptualisation is being applied for each of the three concepts individually, but the goal of this study is to analyse the three concepts together as a whole, as the conceptual field of electrostatics. Hence, it is assumed that all three concepts (electrostatic force, electric field, and electric potential) must have a result above 80% in order to consider that the conceptual field of electrostatics is correctly conceptualised. If one of the concepts is not well conceptualised, there is not enough information to say without any doubt that there is a correct conceptualisation of the conceptual field of electrostatics, and other sources of information would be needed in order to make such an affirmation.

The criterion for the lack of knowledge category was defined considering half or less of the questions answered correctly. For the electrostatic force and electric field concepts, this means 5 or less correct questions. For the electric potential concept, this means two correct answers or less.

The other category, misconception, is defined between these two values, as can be seen in Table 5.

For comparison purposes, Richard R. Hake (1998) defined three intervals to categorise the learning gain in students during a physics course. These three categories are low (0 – 30%), average (30% – 70%) and high (70% – 100%).

The 80% criterion defined in this study may appear to be high as a lower limit for correct conceptualisation. In the same way, the 50% criterion may look very high as an upper limit for lack of knowledge; however, we must recall that we are diagnosing in-service teachers which requires a higher standard since they are supposed to have a correct conceptualisation of the concepts of the course. It is highly likely that a professor with misconceptions or lack of knowledge will generate misconceptions in their students. For example, Alpaydin (2017) sets stricter criteria for his intervals than the ones proposed in this work, considering that there is already a misconception from 15% of erroneous responses.

Again, it is important to remark that due to the intimate relation between the three concepts, the analysis is made for the conceptual field although the results of each concept are presented.

Results and Discussion

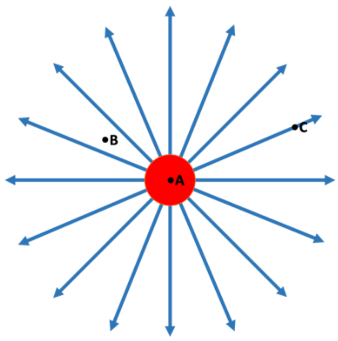
Examples of answers given by professors

Two examples of the responses provided by teachers are presented below in order to illustrate the information obtained to understand and its complexity. The original language was Spanish, and the items with the least text were chosen to minimize information loss during translation.

Question 7 (Electric Field)

First Tier:

The image shows a point charge in red and its respective field lines in dark blue. Three points are also shown identified with the letters A, B and C. At which of these points is there no electric field?



Correct Answer: At point A.
Selected Answer: At points A and B.

Second Tier:

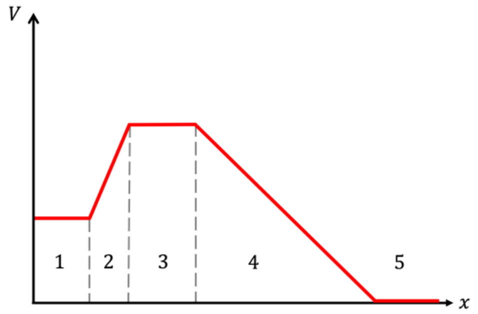
Which of the following statements do you consider to be the best justification for your answer to the previous question?

Correct Answer: It is the point where the field is generated.
Selected Answer: There are no field lines at that or those points.

Third Tier:
Which of the following statements do you consider to be the best justification for your answer to the previous question?

Provided Answer: According to the figure, the blue lines would be the field lines, hence those answers. However, fields are defined throughout space, and an exception is made at zero because there is an infinity according to the theory, so in practice, a zero is placed at the origin. There are theories that remove these types of irregularities, such as Born-Infield Theory, but they are not encountered within the courses in this study.

Question 16 (Electric Potential – Electric Field – Electrostatic Force)
First Tier:
The graph shows the values of electric potential $V(x)$ in 5 regions along the x-axis. In which or which regions can we place a positive charge so that the electrostatic force on it is zero?



Correct Answer: Regions 1, 3 and 5.
Selected Answer: Region 5.

Second Tier:
Which of the following statements do you consider to be the best justification for your answer to the previous question?

Correct Answer: The electric potential is constant and therefore there is no electrostatic force.
Selected Answer: The electric potential decreases to zero in this region and therefore there is no electrostatic force.

Third Tier:
Which of the following statements do you consider to be the best justification for your answer to the previous question?

Provided Answer: There is no electric potential, and the force would be zero.

In the example presented in question 7, we can see in the third tier that the description of the behaviour of the electric field at the location of the source is consistent with accepted scientific knowledge. However, this explanation contradicts the answers chosen in the first and second tiers. This is an indicator of possible misconceptions in the concept of field lines. More information is required to be certain about a misconception in the general concept being assessed, which in this case is 'electric field'. Therefore, the different attributes of each concept are added together to determine if the concept is being conceptualised correctly, which implies that only two of eleven attributes can be wrong, according to the information in Table 4.

Question 17 is an example of a case where there is no doubt about the misconceptions about the attribute being assessed by the question. The answers to the first and second tiers are wrong and the answer to the third tier reinforces the error evidenced in the previous questions. In this case, the attribute being assessed is the relationship between electric potential and electric field (and therefore, electrostatic force).

Table 6 summarises the results obtained in each concept for every professor and the average result for the conceptual field which was calculated as an average of the result for each concept. An average above 80% does not imply a well conceptualised conceptual field, this is achieved only by obtaining an average above 80% in all three concepts.

Table 6. Results for each professor in the diagnostic test.

Professor	Electrostatic Force	Electric Field	Electric Potential	Conceptual Field Electrostatics
1	70%	81.80%	100%	84%
2	40%	63.60%	60%	55%
3	60%	81.80%	80%	74%
4	60%	63.60%	80%	68%
5	80%	72.70%	80%	78%
6	80%	81.80%	100%	87%
7	70%	72.70%	40	61%
8	40%	63.60%	60%	55%
Average	63%	76%	80%	

The results presented in Table 6 are the starting point for a further qualitative description of the teachers' conceptualisation. A few highlights of these results are:

- Only one professor conceptualises correctly the conceptual field of electrostatics, Professor 6, since he is the only one who obtained results of at least 80% in every concept.
- As expected, given the academic background and teaching experience of in-service teachers, the results indicate a predominance of misconceptions over lack of knowledge.
- Professors 1 and 6, who lack a physics degree, achieved the highest scores, as shown in Tables 3 and 6.
- The lowest scores belong to Professors 2 and 8.

Professor 1 has recently taken a professional development course in electricity and magnetism which could explain the good results in the diagnostic test. Professor 6 has taught the course 20 times and took a professional development course in the subject prior to his first time teaching it at the university. Class preparation (textbook reading and didactic material generation) and discussion with the class could explain the gain of knowledge over the years, to the point of properly conceptualising the conceptual field of electrostatics. Another important point to be considered in the result of this professor is the time he has invested in planning the lessons for this subject after 20 times teaching it. According to Großmann & Krüger (2024), it is plausible to assume that high-quality planning correlates with high-quality classroom teaching, although there is not enough empirical evidence that supports this affirmation. However, just as proper planning has a positive influence on the learning outcome, the repetition of the analysis process associated with proper planning can also have a positive effect on teachers' conceptualisation (Contreras et al., 2020).

Professor 2 holds a PhD in physics and has taken the most electricity and magnetism courses during his undergraduate and graduate studies, yet his score was among the lowest. Professor 8 does not have academic formation in physics and has the second-greatest number of electricity and magnetism courses taught.

In the column for electric potential in Table 6 we can see that this is the concept with the best results; however, comparing performance across concepts is not meaningful since the analysis of conceptual fields focuses on the interconnectedness of concepts, not individual mastery.

Conclusion

Obtaining 80% or higher in one concept does not necessarily indicate mastery of that concept or the entire conceptual field, as the assessment emphasises interconnectivity. The diagnostic test was designed to emphasise the relations between concepts, so it would not be correct to make such a claim. For teachers who have a percentage of 80% or higher in two concepts, it could be that there is a correct conceptualisation in one of those concepts; however, to be certain it is necessary to have more information, for example, information obtained through interviews where the teacher can verbally elaborate on the answers given to each question.
A score of 80% or more across all three concepts suggests a generally good understanding of the conceptual field, but potential misconceptions in specific attributes within each concept might still exist and evolve over time.

If the results of Table 6 are related to the information in Table 3, it becomes evident that the experience of teaching the subject can influence a correct conceptualisation.
Given the small number of participants in this study, we can only describe their results but upon further application to more teachers, this diagnostic test can provide a good characterisation with enough information for a better explanation of the results for the group.

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