Probing university students' understanding of electromotive force in Electricity

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The goal of this study is to identify students' difficulties with learning the concepts of electromotive force (emf) and potential difference in the context of transitory currents and resistive direct-current circuits. To investigate these difficulties, we developed a questionnaire based on an analysis of the theoretical and epistemological framework of physics, which was then administered to first-year engineering and physics students at universities in Spain, Colombia, and Belgium. The results of the study show that student difficulties seem to be strongly linked to the absence of an analysis of the energy balance within the circuit and that most university students do not clearly understand the usefulness of and the difference between the concepts of potential difference and emf.

I. INTRODUCTION

Our work deals with the difficulties university students have with the concept of electromotive force (emf). We asked students to consider phenomena involving transitory currents only as well as simple resistive direct-current (dc) circuits. To date there has been little research on the teaching and learning of emf in dc circuits,[1] and we have chosen to investigate this topic for two interrelated reasons. Firstly, it is included in many European Secondary School programmes for students aged 16–18, and in most first-year university engineering and science courses. Secondly, it is a basic prerequisite for explaining how dc circuits and many technological applications operate.

Many teachers have difficulties in using the concept of potential difference in explaining electrical circuits,[2] and many teachers downplay the difference between emf and potential difference.[1] Mulhall *et al.*[2] conclude that both students and teachers have problems describing energy transformations in a circuit within a coherent framework. Both groups admit that they do not have a qualitative idea of the concept of potential difference and tend to avoid it in their explanations. Thus, downplaying the difference may in part be due to an incomplete conceptual understanding. Teachers may also justify this lack of emphasis by stating that in many instances students can obtain a correct answer in numerical exercises without being able to distinguish between the two concepts (for example, because the internal resistance of a battery is negligible). Therefore, they may claim that emphasizing a subtle difference between emf and potential difference may not be worthwhile.

While such statements have some merit, we feel the arguments for making the distinction between emf and potential difference clear are stronger. Firstly, making an analogous distinction between work and potential energy is commonplace in mechanics. Take the example of an object attached to a spring moving on a horizontal surface. Instructors usually distinguish between the work done by a hand pulling on the displaced object and the potential energy thus gained, even if the horizontal surface is assumed to be frictionless. It is therefore hard to argue that it is overly fastidious to distinguish between the work done per unit charge (the emf) and the ensuing potential energy per unit charge (the potential difference) in the context of electric circuits.

Moreover, distinguishing between emf and potential difference in the familiar context of an electric circuit may (and in our view, should) be used to emphasize that the battery is an integral part of the circuit. Of course "we all know this," but in practice students and instructors often talk about "the circuit" when referring to all components apart from the battery (as in, "the circuit is connected to a battery."). A series of "*non-conservative* actions" takes place in the battery, through which energy is delivered to the charge. The emf quantifies these actions as the "work done" per unit charge or the electric energy delivered per unit charge to produce and maintain the electric potential difference that allows an electrical current to flow.[3,4] Thus, the emf pertains to the work done by a non-Coulombic force to move a charge between the terminals inside the battery; potential difference to the work done by a Coulombic field to move the unit of charge between the terminals outside the battery.[5,6]

We also expect that specifically emphasizing the non-conservative nature of the emf could significantly lower the barrier when students encounter emfs that are not due to a battery. It would clearly be advantageous if students were already used to seeing circuits as being driven by a non-conservative force; instead, students are often confronted with a new situation (e.g., a changing magnetic field) that not only leads to a new phenomenon (a non-conservative electric field) but also upsets their view that a potential difference is required for a current to flow.

In this article, we present a number of examples of electric phenomena where the distinction between potential difference and emf is important for a scientific interpretation. We probe in detail the views of undergraduate physics and engineering students on the concepts of potential difference and electromotive force in the context of phenomena involving transitory currents and of simple resistive dc circuits. We provide and analyze data on students' difficulties in learning dc circuit theory that can serve to improve teaching the subject.

There are several studies on students' understanding of concepts such as potential difference and current intensity in electric circuits within the general framework of alternative conceptions research that has been extensively employed in the literature.[7] Many of these studies are based on the experiences of instructors who have pointed out problems with how the material is typically taught.[8] Psillos[9] points out that "In our case, we decided to extend the experimental field to include not only steady states but evolutionary situations as well; to commence conceptual modeling by voltage and energy, introducing these concepts as primary and not relational ones; to present a hierarchy of models capable of answering progressively sophisticated questions." There also have been some empirical investigations on students' difficulties in understanding interpretative models of electrical circuits. Those developed at the university level have principally focused on students' understanding of the role played by potential difference and current intensity.[10]

The present study adds to prior research by examining students' understanding of the concept of emf in dc circuits commonly encountered in introductory physics courses for science and engineering. Students' levels of understanding are described here for two particular types of phenomena: (i) phenomena involving transitory movement of charges due to mechanical work, and (ii) the stationary state of movement of charges in a resistive dc circuit. We consider basic circuits that are not mathematically complex, since mathematical difficulties might mask conceptual difficulties. The focus in this study is on the description of undergraduate students' understanding. A categorization of students' answers has emerged on which teachers can base their teaching strategies to facilitate students' learning. The data also hint at ways to design teaching sequences and to measure the development of conceptual understanding.

II. CONTEXT OF THE RESEARCH AND METHODOLOGY

To investigate undergraduate students' understanding of the concept of emf, engineering and physics students from Spain, Colombia, and Belgium were given a questionnaire after they had studied the subject in class. Four open-ended questions were designed, asking for a careful explanation; the questions are described in detail in Sec. 4. The research was carried out at the University of the Basque Country, at the National Pedagogical University and at the KU Leuven–University of Leuven over the last two years. All first-year students had taken at least two years of physics in high school and they passed the national standard exams in Spain and Colombia to enter University for studying science or engineering. First-year Spanish students received 3.5 hours of lectures and 2 hours in the laboratory per week for 14 weeks (second semester) for electromagnetism. Electrostatics and electrical circuits were taught for 5 or 6 weeks of this course. In Colombia, there were 3 hours of lectures and 3 hours in the laboratory per week for 15 weeks (third semester) for electromagnetism. Electrostatic and electrical circuits were taught for 8 or 9 weeks of this course. In Belgium, students had 4 hours of lecture a week, and 2 hours of recitation (10 weeks). In all cases, lectures were given by experienced teachers of the Physics Department; the Electricity curriculum is similar to those given in textbooks like Tipler & Mosca[11] or Fishbane et al.[12] Spanish and Colombian students answered the questionnaire under exam conditions while the Belgian students took it during a regular lecture without getting credit for it.

The students' answers to the questions were subjected to rigorous analysis.[13,14] The analysis does not focus on correct or incorrect answers but on identifying students' understanding and alternative conceptions. We are aiming at a nuanced understanding of what aspects of emf students understand reasonably well and what aspects are problematic for them. One member of the research team derived a draft set of categories of description for each question based on a reading of the students' answers, and tentatively allocated each answer to one of the draft categories. Three weeks later, the same researcher again read the students' answers and repeated the process. The intra-rater reliability Cohen's kappa coefficient was calculated for this period of time, obtaining a mean value of 0.88 for all the questions, which is satisfactory for a confidence level of 95%. The other researchers carried out the task of allocating each answer to one of established categories independently. Once the answers were classified, the allocations of answers were compared. For the answers from Spain and Colombia the mean kappa reliability coefficient was 0.84 for the questions, which reveals very good consistency in the judges' criteria for setting the categories described. When there was disagreement about category description or allocations of answers, these were resolved with reference to the answers as the only evidence of students' understanding. The focus was on the students' understanding, taking the students' answer as a whole, rather than on the occurrence of particular statements corresponding to a specific category description. An iterative process was used to produce final descriptions of categories that reflected the similarity in understanding among the answers allocated to each category and the differences among the categories.

III. EXPERIMENTAL DESIGN

We designed four questions to assess the students' understanding of emf. The first two questions deal with transitory movement of charges in a context that does not involve an electric circuit. These questions require students to recognize that the work per unit of charge done by mechanical forces is measured by the quantity of emf. The other two questions involve the analysis of resistive direct current electric circuits.

The questions were given to first-year engineering students at the University of the Basque Country (*N*=64) and at KU Leuven (*N*=87), and to first-year physics students at the National Pedagogical University (*N*=50).

Questions 1 and 2 (see Figs. 1 and 2) investigated how students think about emf in phenomena involving transitory currents such as the piezoelectric effect and charge separation in a Van de Graaff generator. Students were asked whether the concept of emf is useful in these contexts and, if so, to explain what the use is. Both questions investigate the students' understanding of the concepts of potential difference and emf within a context that is typically not used in the teaching of electrical circuits.

In order to answer Question 1 correctly, students should know that the mechanical work done on the sides of the crystal produces a separation of charges and a potential difference. The work that separated charges, and in doing so set up a potential difference, is done by non-conservative forces (frictional forces in this case). By the work-energy theorem, the energy is thus created by work done by a non-conservative mechanical force.

Students should use the definition of electromotive force to analyze Question 2. The Van de Graaff device is familiar to all students from the three countries, because they had seen it in lectures or worked with it in the laboratory. As with the kitchen lighter, the mechanical work per unit of charge done by non-conservative frictional forces in the Van de Graaff generator is represented by emf, and not by potential difference.

Question 3 (see Fig. 3) specifically aims to study whether students think of the circuit as a whole, including the battery. This question is the most "subtle" (or even "useless") if all one cares about is obtaining correct equalities, but we consider it the simplest possible setting for discussing in detail the difference between emf and potential difference. Although we did not expect our students to grasp all of these subtleties, the question elucidated some important problems, as discussed in Sec. 5.

We use the spring analogy again to illustrate that analogous subtleties are routinely incorporated in mechanics courses. Consider a problem where an object attached to a spring is pulled by a hand. The object is then released and returns to the equilibrium position, which it reaches with speed *v*. Looking at the entire process, the hand does work; this work is converted first to elastic potential energy, then to kinetic energy. If we asked students about the energy balance in this case, they could write a) $E_{\text{pot}} = mv^2/2$ or b) $W = mv^2/2$. Both answers give a correct equality, and both may be used to assess in what form the energy manifests itself at two points. The right-hand-sides of these equalities represent the kinetic energy of the object when it returns to the equilibrium position. In answer a) the left-hand-side represents the elastic potential energy of the object at the instant it is released; in answer b) it represents the work done by the hand during the process of stretching the spring. It is only because there is no friction that the work done by the hand and the elastic potential energy are equal; if we allow for friction, the work done by the hand is converted into thermal energy plus elastic potential energy. From a teaching point of view, the key observations to be taken from this analogy are (1) that students and instructors alike would think it natural and fruitful to distinguish between potential energy and work in this case, and (2) that the balance between potential energy and kinetic energy concerns two *instants*, while the considering work and kinetic energy pertains to a *process*.

Returning to Question 3, the battery does work that is first converted to potential energy and then to thermal energy. The work done per unit charge ε is equal to the electric potential energy per unit charge ΔV, which is in turn converted to thermal energy per unit charge IR. Both answers—a) $\Delta V = IR$ and b) $\varepsilon = IR$—give a correct equality. The right-hand-sides of these equalities represent the thermal energy per unit charge in the resistor. In answer a) the left-hand-side represents the electric potential energy at the terminals; in answer b) it represents the work done per unit charge to move the charges from one terminal to the other inside the battery. It is only because there is no internal resistance that the work done by the battery is equal to the electric potential energy; for non-zero internal resistance, the work done by the battery is converted into thermal energy plus electric potential energy. Thus there are three arguments for distinguishing clearly between emf and potential difference: (1) emf is non-electrostatic, unlike potential difference; (2) when the two quantities are equal, it is purely circumstantial; and (3) considering potential difference rather than emf does not take into account the entire process or the entire circuit but only the part that lies outside the battery terminals.

The aim of Question 4 is to differentiate between emf and the potential difference in a simple dc circuit. The question reads: "If the same battery is connected to different circuits, which quantity remains constant: the potential difference between the terminals of the battery or its electromotive force? Explain." To explain the emf correctly, students should recognize that the potential difference is the work done per unit charge by conservative electric forces when the charges move from one point to another in a circuit, while the emf measures the work per unit charge carried out by non-conservative forces within the generator to create a potential difference. Hence the emf is characteristic of the battery and remains constant; in cases where the resistance of the external circuit is smaller than or comparable to that of the battery, the potential difference will change significantly.

IV. RESULTS AND DISCUSSION

The results of the students' answers to the four questions are shown as percentages in Table I. It is *not* our aim to examine differences between the universities. Even though we think that the preparation of the students is similar, we cannot (and do not want to) assess the role played by, e.g., language issues, differences between lecturers, and conditions under which the data were obtained. The main message to be taken from our data is that the categorization that has emerged appears to be sensible in three different educational systems, and that in each of the educational systems different questions on emf trigger different responses. One of the strongest findings is that (except for Question 4 in KU Leuven) fewer than 20% of answers were coded as "correct with correct reasoning" (category A), with the average closer to 10%. The results show that the majority of students confuse emf and potential difference, and they do not have a conceptual understanding of emf.

[TABLE 1]

A. Categorization of student responses

The four questions present different contexts and the diversity of students' answers shows that the context strongly influences their reasoning. We identified three common categories of reasoning that emerged when students answered each question, also shown in Table I. There is a category in each question that includes *all* of the elements that correspond to an expert understanding of the concept of emf (category A), "Correct understanding of emf." Answers in this category identify emf as the work done per unit of charge in reorganising the charges and generating a potential difference.

In category B, "emf as a 'force' that moves charges," emf is considered a mechanical force. The majority of the answers explicitly state that emf is a force that does work, rather than the work done per unit charge. In both UPN and UPV-EHU, about half of the answers to Question 1 are in this category, but the percentage decreases to about 12% in the context of electric circuits (Question 3 and 4). We infer from this that not only the name of the quantity but also the context in which the question is set may generate a predisposition to consider emf as a force.[15] Answers in this category are typically incomplete rather than incorrect: there is a focus on the force concept and students give it the capability to do "work" to move charges, but they do not link emf and potential difference.

In category C, "Confusion between emf and potential difference," students attribute the same properties to emf and potential difference. Here students do not distinguish between the different roles played by emf and potential difference in the context of electric circuits. For example, some students state that Ohm's law describes the energy balance of the entire circuit. When the context did not involve an electric circuit (Questions Q1 and Q2), few students in UPN and UPV-EHU used the concept of potential difference. This suggests that even though these students found it difficult to distinguish between emf and potential difference, they did not consider them equivalent in this context. However, at KU Leuven the situation was reversed, with more students thinking of emf as a potential difference but fewer thinking of emf as a force. Again, we stress that the data confirm the validity of the categorization—we are not interested in examining the differences between the institutions, even though in this case it seems clear that differences are likely to reflect choices made by individual lecturers.

Answers in category D, "incorrect analysis of emf," do not mention the role played by emf or use badly memorized definitions.

B. Commentary

Category A: Correct answers

Only a minority of students recognizes that emf is the quantity that measures work done per unit charge by the device or the battery that supplies electrical energy (category A). The fraction of correct answers depends on the context.

Category B: Electromotive force as a force that does work or as energy

Questions Q1 and Q2 were designed to test students' understanding of the concept of emf in contexts different from that of an electric circuit with a battery. They were asked about the adequacy of analyzing the situation using the concept of emf. There is a minority (about 10% in category A) associating emf with energy or the transformation of energy through the device or the battery. A significant number of responses show that students are not able to construct a correct causal connection between force, mechanical work, and work done per unit of charge. In the students' answers to Question 1, explanations explicitly identify emf as a force that does work. In Question 2, the majority of the answers identify emf as the frictional force within the Van de Graaff. For example:

> "The emf is the value of the force made by the device and this force is necessary for moving the electrons. The student's argument is not correct; it can be considered as a source of emf because there is a force for moving the electrons" (Q1, UPV-EHU)

> "I think the student is wrong because the emf is the value of force applied to two opposing sides " (Q1, UPN)

> "The student is wrong as he considers the emf as a voltage, while it is a force." (Q1, KU Leuven)

> "For producing the charge distribution in the generator an electromotive force is necessary. The electromotive force will move the electrons for producing the sparks. The emf force is not easy to calculate because it is the frictional force produced by the Van de Graaff (Q2, UPV-EHU.)

Category C: Tendency to confuse the electromotive force with potential difference

Two contexts involving a continuous current circuit were designed (Questions Q3 and Q4) to study students' reasoning on the energy balance in the circuit. The questions cannot be answered completely without using the concept of emf. In this context, the tendency of the majority of students (category C) is to attribute the same characteristics to emf and potential difference, to the extent that they provide no meaningful distinction between the concepts in the context of an electric circuit with a steady current. For example, in response to Question Q4 one student states:

> "In this case, talking about potential difference or emf is the same, since the reference is to the energy it takes to move the electrons through the circuit." (Q4, UPN)

> "Both, because emf = potential difference" (Q4, KU Leuven)

In response to the same question another student states:

> "If we measure the battery terminals with a voltmeter we obtain its potential difference, yet at the same time that potential difference is the voltage of the battery, as in its electromotive force, since the electromotive force is a potential difference. Therefore, the two remain constant (they are the same)." (Q4, UPV-EHU)

Some students attribute properties of emf to potential difference and vice versa. For example:

> "The potential difference remains the same because it is the same with all circuits, whereas the emf within the battery must increase in order to take all the circuits to the same potential

difference; this is reflected in the increase in current that travels through each circuit." (Q4, UPN)

"The potential difference remains the same. The emf will vary with the load in the circuit" (Q4, KU Leuven)

In every question asked, confusion between the properties of emf and those of potential difference (see category C in Table I) shows up, although students justify that both concepts have the same physical meaning in different ways:

1) Formula-based justification that attributes the same physical meaning to two different concepts that have the same numerical value within a given situation. The students appear to put more trust in the quantitative correctness of the equation than in logical conceptual arguments. For example:

"To conserve energy, the energy balance of the circuit is determined by $\varepsilon - Ir - IR = 0$. As there is no internal resistance $\varepsilon = IR = \Delta V$. Then the potential difference and the emf are the same to measure the energy from the circuit. So the correct option is c)." (Q3, UPV-EHU)

"The potential difference remains the same. The emf depends on the current that passes through the battery ($\varepsilon = V_{ab} - Ir$)." (Q4, KU Leuven)

"ε = emf, I is current, R = resistance. The emf equals the voltage over the poles – internal resistance × current ($\varepsilon = V_{ab} - Ir$), Ir is negligible, so $\varepsilon = V_{ab}$." (Q3, KU Leuven)

"V = potential difference between poles, ε = emf, I is current, R is resistance. As ε only differs from V by the internal resistance, and $r = 0$, both equations are equivalent." (Q3, KU Leuven)

2) Belief that the concept of emf can only be defined in an electric circuit with a battery. For example:

"The concept of electromotive force can only be applied in circuits with batteries or electric motors." (Q2, UPN)

"The electromotive force is a property of the battery in a circuit, so here there is no emf." (Q1, UPV-EHU)

3) Functional fixation with Ohm's law. Functional fixation of reasoning means that students tend to use a single strategy that generally involves specific and direct application of a "recipe," which has no global consistency with the theoretical framework.[16] Students appear to use Ohm's law merely as a calculational convenience without analyzing when or whether it applies. Some students considered Ohm's law to be something applicable not only to the resistive circuit components, but to the entire circuit, and use it to evaluate the energy balance of the entire circuit. For example:

"Ohm's law represents the energy balance for the circuit. The correct option is c)." (Q3, UPV-EHU).

"V = voltage / I = current / R = resistance. $\Delta V = IR$ is Ohm's law, which is based on conservation of energy and voltage = energy." (Q3, KU Leuven)

4) The belief that potential difference produces electromotive force. Throughout the questionnaire many students assumed that the battery or the Van de Graaff generator produces a potential difference in circuits with a continuous current, and that this potential difference produces the electromotive force. For example:

> "The battery produces a potential difference and this stays constant because if the circuit varies, the electromotive force varies since this is what does the work of delivering charges." (UPV-EHU, Q4).

> "Both emf and potential difference are related. First there is a potential difference which produces electromotive force. In this question both are constant." (Q4, UPN)

V. CONCLUDING REMARKS AND IMPLICATIONS FOR TEACHING

We have found common types of misunderstanding in three countries and similar reasoning patterns by students when answering questions related to emf and potential difference. The students in these three countries have similar physics backgrounds in secondary education, use similar textbooks, and are exposed to similar lecture-based teaching strategies.

Some of our results are supported by findings in previous studies on students' understanding of electricity. For example, the tendency of students to use Ohm's law as a general principle of electricity or their difficulties in explaining the working of the electrical circuit in its entirety.[17,18] Moreover, in our study we found evidence that the students from the three countries have a vague understanding of electromotive force. When confronted with qualitative questions, students show a reluctance to explain the meaning of emf. We strongly believe that this reluctance is due to a lack of understanding of the concept of emf and difficulty in distinguishing it from potential difference.

Students' difficulties with learning the electromotive force concept in electric circuits seem to be strongly linked to the absence of an analysis of the work done on charges within the circuit and the energetic balance of the circuit. In this regard, most students do not clearly understand the usefulness of the concepts of potential difference and emf, neither in situations involving transitory movement of charges nor in situations involving continuous movement. In all cases, we found that the vast majority of students do not understand that the concept of electromotive force is the quantity that measures the work per unit of charge done by non-conservative forces to supply electric potential energy to the entire circuit (both the exterior and the interior of the battery).

Many of the students' difficulties in analyzing the role of emf appear to stem from misinterpreting its physical meaning. Many students see emf as a "force" or an "energy" that drives charges through the conducting wire. Lack of an adequate meaning for the concept of emf causes many students to confuse it with the concept of potential difference. Often the students attribute properties of potential difference to emf and vice versa. Similarly, in electric circuits with a continuous flow, to calculate the energy balance in the entire circuit the students make an overgeneralization by applying Ohm's law to all parts of the circuit.

In traditional teaching approaches that tend to present theory as facts, the conceptual and mathematical complexity of potential and potential difference is exacerbated by the rapid introduction of these concepts in two different contexts: electrostatics and electrodynamics. The standard introductory course introduces electric potential in the chapters on electrostatics. Attention is usually paid to computing the potential function for various discrete and continuous charge distributions.[5,6] These concepts are quickly followed by the concept of electromotive force in the context of dc circuits. The electromotive force concept is defined as a property of the battery and it is introduced mathematically by Kirchhoff's loop rule. However, one rarely finds explicit relations in the textbooks for using both electric potential and electromotive force as two quantities that measure work done by different types of fields (conservative and non-conservative fields). For example, the emf measures the potential energy given by the battery to a unit of charge for moving through any section of the circuit. This process takes place in the battery by chemical reactions, which are called "non-conservative actions".[19] This non-conservative action gives the charges electrical potential energy and produces the potential difference between the poles of the battery.

Our findings suggest that for a teaching sequence to be successful, it must help students understand that emf and potential difference are different concepts, most likely through considering work and energy. Our findings also suggest that many students already understand that emf "drives" the transitory and steady-state behavior, but in an unsophisticated way that often does not distinguish emf from force, energy, and potential difference. Nevertheless, emf as a driver is likely to be a productive starting point. Moreover, students should be led to understand that Ohm's law is not fundamental to electric circuits. We will turn our attention to the design and implementation of fruitful teaching sequences in future work.

In summary, the electromotive force is a quantity that measures the energy transfer (from battery to charges within the circuit) related to a non-conservative field.[20] This definition involves complex ideas and students can easily be overwhelmed by the rapid introduction of abstract ideas, which could explain the poor understanding found in our study. We found that many students do not have a deep conceptual understanding of the concept of emf, and more importantly, we were able to categorize the different problems students encounter with this concept. We believe that the detailed description of the students' errors in the categories could help physics teachers as well as physics education researchers to address the conceptual knots such as the crucial role of the work done in the circuit.

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References

[1] J. Guisasola, A. Montero, and M. Fernández, “Concepciones de futuros profesores de ciencias sobre un concepto ‘olvidado’ en la enseñanza de la electricidad: la fuerza electromotriz” (Pre-service teachers' conceptions on a concept ‘forgotten’ in the teaching of electricity: electromotive force), Ens. Cien. **23**, 47–60 (2005).

[2] P. Mulhall, B. McKittrick, and R. Gunstone, “A perspective on the resolution of confusions in the teaching of electricity,” Res. Sci. Educ. **31**, 575–587 (2001).

[3] H. Härtel, “The electric circuit as a system: A new approach,” Eur. J. Sci. Ed. **4** (1), 45–55 (1982).

[4] J. Guisasola, I. Garzón & Zuza, K. “The influence of the history of science in designing learning indicators: Electromotive force in dc circuits,” J. Sci. Educ. **14**, 4–8 (2013).

[5] F. Reif, “Generalized Ohm's law, potential difference, and voltage measurements,” Am. J. Phys. **50** (11), 1048–1049 (1981).

[6] R.N. Varney and L.H. Fisher, “Electromotive force: Volta's forgotten concept,” Am. J. Phys. **48** (5), 405–408 (1980).

[7] L. McDermott and E. Redish, “Resource Letter: PER-1: Physics Education Research,” Am. J. Phys. **67**, 755–767 (1999).

[8] S. Stocklmayer and D. Treagust, “A Historical Analysis of Electric Currents in Textbooks: A Century of Influence on Physics Education,” Sci & Edu. **3**, 131–154 (1994).

[9] D. Psillos, “Teaching introductory Electricity,” in C*onnecting Research in physics Education with Teacher Education* vol. 1. Edited by Andrée Tiberghien, E. Leonard Jossem, Jorge Barojas. I.C.P.E. Book, available online at <http://www.physics.ohio-state.edu/~jossem/ICPE/E4.html> (1998).

[10] L.C. McDermott and P.S. Shaffer, “Research as a guide for curriculum development: An example from introductory electricity, Part I: Investigation of student understanding,” Am. J. Phys. **60**, 994–1003 (1992); Erratum to Part I, Am. J. Phys. **61**, 81 (1993).

[11] P.A. Tipler and G. Mosca, *Physics for scientists and engineers* (Fifth edition, Freeman and Company, New York, 2004)

[12] P.M. Fishbane, S. Gasiorowicz, and S.T. Thornton, *Physics for scientists and engineers* (Second Edition, Prentice-Hall, 1996)

[13] L. Cohen, L. Manion, and K. Morrison, *Research Methods in Education* (6th Edition, Routledge, London, 2007) Chap. 24.

[14] M. Watts, G. Gould, and S. Alsop, “Questions of understanding: Categorising pupils' questions in Science” SSR, **79**, 57–63 (1997).

[15] N. Legault and D. Peschard, “Concerning the electromotive force (or emf),” Phys. Teach. **39**, 69 (2001).

[16] J. R. Anderson, *Cognitive Psychology and Its Implications* (Freeman, New York, 1990)

[17] E. Bagno and B. Eylon, “From problem solving to a knowledge structure: An example from the domain of electromagnetism,” Am. J. Phys. **65** (8), 726–736 (2007).

[18] A. Benseghir and J.L. Closset, “The electrostatics-electrokinetics transition: historical and educational difficulties,” Int. J. Sci. Ed. **18** (2), 179–191 (1996).

[19] R. Chabay and B. Sherwood, *Electric and Magnetic Interactions* (2nd Edition, Wiley, New York, 2007)

[20] P. Lorrain, D.R. Corson and F. Lorrain, *Fundamentals of electromagnetic phenomena* (W.H. Freeman and Company, New York, 2000).

Categories	Q1				Q2				Q3				Q4			
	UPN (N=50)	EHU (N=64)	KU Leuven (N=87)	all (SE) (N=201)	UPN (N=50)	EHU (N=64)	KU Leuven (N=87)	all (SE) (N=201)	UPN (N=50)	EHU (N=64)	KU Leuven (N=87)	all (SE) (N=201)	UPN (N=50)	EHU (N=64)	KU Leuven (N=87)	All (SE) (N=201)
A.	6%	7%	2%	5% (2.1)	8%	8%	13%	10% (2.3)	10%	10%	5%	8% (2.3)	20%	15%	37%	26% (9.4)
B.	50%	47%	8%	31% (19.1)	20%	17%	8%	14% (5.1)	8%	2%	13%	8% (2.1)	14%	17%	1%	9% (6.9)
C.	4%	15%	34%	20% (12.3)	6%	27%	12%	15% (8.8)	54%	50%	58%	54% (3.2)	22%	40%	16%	25% (10.1)
D.	24%	17%	34%	26% (6.9)	46%	37%	57%	48% (8.1)	20%	16%	13%	16% (2.8)	26%	14%	20%	20% (4.8)
NA/I	16%	14%	22%	18% (3.3)	20%	11%	10%	13% (4.4)	8%	22%	11%	14% (6.1)	18%	14%	26%	20% (1.6)

Table 1. Results obtained in the questionnaire in the three universities. Shown are the prevalence of each category of answers for each question in each university and the average of percentages and standard error (SE) for each question and category in the three universities. Category A: Correct understanding of the meaning of emf; Category B: emf as “force” that moves charges; Category C: Confusion between emf and potential difference (reasoning based on a formula; emf is the same as potential difference, or Ohm's law describing the energy balance in the entire circuit); Category D: Incorrect reasoning based on poorly assimilated knowledge students have remembered, or no use of the concept of emf; NA: No answer or incoherent.