How much have students learned? Research-based teaching on electrical capacitance

Jenaro Guisasola, José L. Zubimendi, and Kristina Zuza
Department of Applied Physics, University of the Basque Country, San Sebastian, Spain
(Received 29 March 2010; published 12 July 2010)

We examine the pedagogical suitability of introducing a teaching sequence for the concept of electrical capacitance within the context of charging a body. This short sequence targets first year university students and was designed following students' common conceptions on this topic. The evaluation is made by comparing the results with a control group using written questionnaires. The results show that the elements within the sequence help students to establish a connection between the movement of charges (microframe) and the energetic analysis of the system (macroframe).

DOI: 10.1103/PhysRevSTPER.6.020102 PACS number(s): 01.40.−d, 01.50.−i, 84.37.+q, 84.32.Tt

I. INTRODUCTION

The concept of charge and the properties of charged bodies are an important part of physics instruction at many different levels. Students learn about the idea of charging in elementary school and gradually integrate more complex ideas to interpret electrical phenomena. Studying the models to interpret electromagnetic phenomena is a rich area, providing a solid basis for understanding everything from the electromagnetic nature of matter to the basis of contemporary technology. The structure of the electromagnetic nature of matter is both beautiful and useful. Furthermore, electromagnetic theories provide a good context for teaching scientific reasoning skills such as model-building and drawing relations between macroscopic phenomena and microscopic theories [1].

In physics and engineering graduate schools, students continue to learn more detailed theories for describing the electrical proprieties of charged bodies. The calculus-based physics course taken by engineering students at the University of the Basque Country is typical among Spanish universities, and similar to corresponding courses in the United States and elsewhere. Usually the electricity programme starts by studying the properties of charged matter (conductors and insulators, polarization, charge by induction, charging and discharging bodies), conservation quantization of the charge, Coulomb's law, and forces involving multiple charges. Next the ideas of field, flux, Gauss's law, concept of potential and potential difference are taught [2]. These ideas are followed by electrical capacitance and capacitors which are often presented quickly within a week of the course. However, there is not usually a teaching sequence which analyses the efficiency in the processes of charging bodies and no explanatory model is given for these processes including the concepts of charge, potential difference, and electrical capacitance. Students can easily be overwhelmed by the speed that these abstract ideas are introduced and they are usually not given sufficient practice to be able to apply these concepts reliably, or to discriminate between them [3,4]

It is essential to measure of the efficiency of the processes to charge bodies in the model explaining the fundamental electrical process, for two reasons. First, the processes to charge a body cause an initial transition from electrostatics to electrokinetics, even though the context is not a conventional electrical circuit. The explanatory model requires significant knowledge of the electrical nature of matter and brings together the concepts of electrical charge and electrical potential. Second, most frequent technological applications for electrical processes require bodies which are capable of accumulating a lot of charge at a low cost. This was a tricky relevant historical problem which required a new concept to be introduced: electrical capacitance [5].

In this paper, we will focus on the model explaining the efficiency of processes charging bodies and the concept of electrical capacitance. This topic is in the physics syllabus at the end of electrostatics before studying electrical circuits [2,6]. Learning which includes understanding the concept of electrical capacitance implies not only knowing how to calculate using its formula, but knowing that it is necessary to be aware of what goes on during the process of charging a body. In order to relate "operational" reasoning based on a rule or formula, for example $C=Q/V$, to "causal" reasoning based on what happens and changes during the process of charging a body, it is necessary to implement systemic reasoning [7]. As Roller and Blum [8] indicate"… capacitance is a property of the system that depends on the geometry of the field lines between the conductors, that is altered when the connections are modified" (p. 1051). This reasoning is based on considering interactions between the different parts (battery-environment-body to be charged) and the changes which take place (passage of current) which may explain the "mechanisms" enabling a new equilibrium to be established. Viennot [9] (2001) showed that the energy model provides a more general and less fragmented vision of how the current passes round a circuit, but it is necessary to teach it explicitly so it can be used by the students. Discussing the potential electrical energy acquired by a body on being charged is due to the work carried out by the environment during the process. Talking about the potential energy of a charged body and the environment enables us to establish a "mechanism" to explain the new equilibrium achieved [10].

One controversial question in teaching the concept of electrical capacitance is whether and how to teach it at high school level. This is a fiercely debated topic among Spanish high school teachers and in fact, in the last Spanish science curricular reform at high school level, standards state that students should be able to explain the movement of charges in the conductors and the processes of charging bodies. It proposes an explicative model for the processes of charging bodies based on electrical forces, but does not state that this occurs through the concept of electrical capacitance. We therefore have to consider, at least within the framework of education in Spain, that students will study the concept of electrical capacitance in physics courses for the first time in their first year at university. This implies that it may not be assumed that students are familiar with the processes for charging bodies or with apparatus such as capacitors. So, in Spanish calculus-based university physics courses, in the first chapter on electricity, students usually start using a qualitative model based on attraction and repulsion charges to explain charging and discharging. However, in this paper we do not deal with this topic, the teaching-learning problem that is analyzed here corresponds to the part of programme that deals with the problem of efficiency in charging bodies and the explicative models which include the concepts of charge, potential difference and electrical capacitance [2,6,10]. This means that the teaching sequence that we present here tries to lead students from a first direct explicative model based on electrical forces to another one in which it is necessary to consider the concepts of potential difference and electrical capacitance. This does not mean that the first model is not useful but the explicative model becomes more complex. We can see similar transition in mechanics when we learn about the concept of energy of position or potential energy which is extremely useful, but it does not mean that the concept of gravitational force is invalid. On the contrary, both are complementary. However, as we can see in the next section, the model based on energy or potential difference presents several difficulties to students since the model of forces is more a direct causal model than the energy model [11].

II. PREVIOUS RESEARCH AND STUDENTS' DIFFICULTIES IN LEARNING ABOUT ELECTRICAL CAPACITANCE

Several studies point out that undergraduate students have difficulties when analyzing how matter behaves during electrical interaction [12–14]. Lack of knowledge about the electrical nature of matter has been mentioned as one of the reasons for these problems occurring. Park *et al.* (2001) show that 50% of 50 university students believe that an electric charge cannot flow through insulators. The study showed a lack of understanding about dielectric polarization. This result can also be found in other research about students' responses to interpretation of polarization phenomena [15,16]. Several investigations confirm that most students lacked knowledge regarding the meaning of terms such as potential and potential difference, which they frequently use as isolated and undefined concepts [17,18]. Students and some teachers avoid using these terms, even if they are specifically required to do so [3,19]. Instead, they use terms like charge or electricity. Research shows that the concept of potential difference is masked by the concept of charge, hence losing its own meaning; as has also been mentioned by Benseghir and Closset [4].

Regarding the processes of charging bodies, a first explicative model based on electrical forces shows that this is a direct causal mechanism to explain the phenomena. But the problem at first year university level arises when the efficiency of the charging is analyzed and it is necessary to add more concepts such as electrical potential and capacitance. Here students have to complete the first model based on electrical forces with field and energy concepts [7]. The concept of capacitance is related to the electric potential or electric energy, as Feyman [20] states "the potential difference between any points is proportional to the charges… the coefficient of proportionality is called capacitance" [p. 6–18]. However, most undergraduate students explain these processes as passing charges from the generator to the body to be charged. They explain that these charges move because of the difference in the amount of charge between them. In these explanations it is not necessary to discuss the difference in potential between the bodies to explain the charging process. Students only take into account the size of the objects and the quantity of charge that they have but they do not analyze the geometrical shape of the object and the charge distribution within it. Reasoning in this way, students identify quantity of charge and capacitance and so, the capacitance concept has no meaning for uncharged bodies [21]. Furthermore, a significant number of students unintentionally use the formula for electrical potential and electrical capacitance. It seems that when failing to make any sense of concepts, students take refuge in operative definitions and base their reasoning on them [9]. This study aims to overcome these students' difficulties introducing a more complex model step by step which completes the causal mechanism regarding the efficiency of charging bodies. For this reason at the start of the sequence (sections A, B, and C in Table I) the students are set to work once again on the processes of charging and they are given opportunities to consider these processes, although now using the concepts of charge, field and potential that they have studied recently in previous chapters. This model based on electric energy, although necessary, is not evident for students, as Park and Kim [22] showed whenever students changed their previous ideas; they almost always introduce a new idea to explain contradictory observations. In other words, contradictory observations or new observations alone, without any new or complementary explanatory model, could not change previous ideas.

Finally, research shows that avoiding discussion on topics likely to lead to misconceptions does not work [23]. It is much more effective to explicitly address the problem students are likely to encounter. This approach is important when discussing the teaching electrical capacitance and the model explaining the processes of electrically charging bodies at the university level. Students learn the properties of charged bodies in Secondary School and in popular culture, so they start university courses with preconceived ideas about electrical processes, whether we like it or not.

III. STUDY

Our basic research question is: How can we design a teaching sequence for electrical capacitance and implement it effectively? In accordance with Meheut and Psillos [24], we understand a "teaching-learning sequence" to be a widely

TABLE I. Problem based structure of the sequence on "How are bodies charged? How can we charge them more efficiently?"

Problem sequence	Science concept that must be learnt	Scientific explanations that must be understood
A. Why are we interested in accumulating charges in bodies?	**A.** Science is interested in natural phenomena and their social implications.	
B. How is a charge stored in a body?	**B.** When tackling problems, science starts by setting them out and looking for a solution.	**B.** Descriptive study of charging conductive and dielectric materials
What is needed to charge a body?	Become familiar with empirical observations or information on the phenomena being studied.	Acquiring a preliminary conception of the task to be studied: What is the connection between the accumulated charge and the potential acquired by a body? Differentiation between the concepts of charge and potential.
Is there a limit to the process of charging a body?	Working from organizing the experimental information, producing hypotheses and selecting the right strategies, drawing up an initial explanatory model.	Constructing a "systemic model of difference in potential" (body, generator, medium) which explains the charging process on the basis of the work carried out to charge it.
C. What makes it easier or more difficult to charge a body?	**C.** Completing the explanatory model and defining new concepts	**C.** Establishing the concept of the electrical capacitance of a body as the greater or lesser facility for storing a given charge by carrying out a given task. Operational definition of electrical capacitance.
What happens when we charge bodies of different sizes and shapes?	Testing the proposed model	Electrical capacitance is a property of a body which depends on its shape, size and environment.
D. How can we increase the yield from the charging process?	**D.** Working from organizing computer simulation information, producing hypotheses and selecting the right strategies, working the explanatory model.	**D.** Extending the explanatory model to the case of capacitors.
What happens when a conductor is placed near another one which we want to charge?	Testing the proposed model. Designing and running experimental checks or using simulations.	Using the electrical capacitance model to optimize storage of a charge in a capacitor by introducing a dielectric between its plates.
What happens when different materials are introduced between the plates of a capacitor?	Evaluating the model's validity and limitations.	

used term to denote the close link between the proposed teaching and expected student learning outcomes of a research-based, topic-oriented sequence. The approach presented here falls within a line of research that investigates teaching and learning in detail (involving a single topic sequence) rather than as a whole curriculum, over one or two years.

The context of the study is a transformed calculus-based physics course for first-year engineering degree students, taught by the authors over three years (2005–06, 2006–07, 2007–08), and using the newly designed pedagogical materials. The course format provided an interactive learning context [25]. The instructional practice is consistent with alternative instruction within the framework explained by Dancy and Henderson [26] in relation to instructional practice (p. 010103–3) and instructional conceptions (p. 010103–4). The teaching materials promote a highly interactive environment during the discussion sessions. Much of the course experience involves a cooperative learning model for students. In the same way, material development is consistent with a constructivist view of knowledge development. The traditional lectures (25% of the overall course) take place after the discussion sessions.

The course content emphasized connections with social scientific problems and everyday technological applications, scientific reasoning and qualitative approaches to concepts and theories. The teaching material for the transformed course is available over the Internet as University of the Basque Country Open Course Ware [27] for the students at our university. We also chose control groups (Group C, two classes), that took the same syllabus but followed a course format with lectures. The control students do not normally have the opportunity to participate actively and are limited to taking notes from the teacher's explanations.

Table I demonstrates how electrical capacitance was tackled in the transformed course. As we mentioned above, the principal objective of the teaching unit design is to make sense of the concepts studied in preceding chapters such as charge and electric potential in relation to the efficiency of charging bodies and construct a more complex causal model which includes these concepts. Students should see the objective of what they are doing at any time during the teaching and learning process. If that is the case, the process of teaching and learning will probably make (more) sense to them and it then becomes more probable that they will construct a view of physics as an interconnected web of concepts. As reported by Albey [28] this is not a self-evident objective. Setting a problem (e.g., Why is it interesting to study the processes of electrical charge on bodies?) leads to establishing the objectives to be achieved when studying the sequence and this problem is defined progressively, as occurs in scientific work, and concludes with specific problems which define the common theme of the sequence.

In the traditional classes (control groups) the instructor began by explaining the definition of a capacitor as a pair of conductors separated by empty space or by nonconducting material. He then explained capacitance as a proportional constant between the capacitor charge and the potential difference; followed by typical examples of calculating capacitance for two parallel plates capacitor, a spherical capacitor and a cylindrical capacitor. Finally the instructor explained the energy in capacitors, capacitors in parallel and series, and dielectrics in capacitors. Typical examples and problems from the textbook [2] followed. The students from the control groups are enrolled in the second semester (electricity and magnetism) of a traditional calculus-based introductory physics course taught by two teachers from the department of Applied Physics who have more than ten years of experience teaching introductory physics courses; they also do research in physics (electromagnetic materials area) at the University of the Basque Country. Students attend the same timetable and syllabus as the experimental students, three 50 min lectures each week with approximately 75 students, all of whom are taking engineering degrees. Control students do not normally have the opportunity to participate actively during the lectures, but they have 2 h each week to ask to teacher about solving problems from the textbook. These tutorials are limited to teacher explanations for the students' difficulties in solving problems, so they are not based on the model pioneered by the Physics Education Group at the University of Washington. As mentioned, the same amount of teaching time was devoted to the topics in both the experimental and traditional classes. In our university, physics laboratory work is independent from lectures, follows a different timetable and is given by different teachers. Nevertheless, students do standard electromagnetic experiments during the course.

During the sequence students carried out the following kinds of activities:

(a) *Social implications of the topic*, which tries to make the problem interesting for the students, so that they become involved in solving it and, in addition, it makes them aware of the objectives being proposed.

(b) *Group work*, where students work in small groups, evaluating their individual ideas, adding new ideas, and reaching a consensus or disagreement. When students are working in groups, the teacher takes a backseat, supervising the students, because they need time to think for themselves and clarify their ideas.

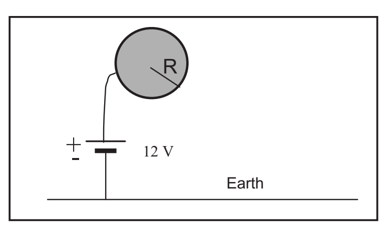
(c) C*lass discussion and teacher guidance*, the teachers guided a question-posing approach. This approach puts students in a position where they are able to extend their knowledge and abilities in a certain direction which helps to solve the problem. When the students have finished their work, there is a round table discussion, directed by the teacher. During the discussion, each group must justify their answers. Ultimately, there will be one or several explanations for each problem. The teacher will insist that every explanation must be justified by evidence, or scientific arguments. Each group's representative presents the group's consensus; all the ways of solving the task are discussed, guided by the teacher and a classroom summary is formulated.

(d) *Individual report*, where each student individually states how the task was solved, specifically explaining how the results were justified. In the following lesson, the teacher discusses the students' reports.

As an example, we are going to show some activities for the different steps in Table I. In step B of the sequence (see Table I), we give students the chance to interpret the processes of electrical charge of bodies from the idea that charges only move when there is a potential difference as they learned in Electrostatics. For example, one of the paper and pencil tasks in this step of the sequence is as follows:

Task. Describe the process for charging a conductive sphere with radius R, connected to the positive terminal of a 12 V battery, when the negative terminal is grounded.

Calculate the work necessary to charge the conductive sphere with charge Q. What does this work represent?



Some student comments, made in the discussion session after solving the task in groups, are given below:

> Representative from Group 2: Electrons will pass from the battery to the sphere until no more can be accumulated or the battery is exhausted. We do not know how to calculate the work, we would have to know the power with which the electrons are thrust and the space traveled.

> Representative from Group 6: We do not agree as we have seen that electrons move toward increasing potentials. At the start of the process there is a difference in potential between the positive terminal of the battery (+12 V) and the sphere (0 V), therefore electrons pass until the potential of the sphere is +12 V. When the potentials become equal no more electrons can pass.

> Representative from Group 8: We agree with Group 6's explanation as it allows the work carried out to be calculated, whereas Group 2's explanation does not. If we consider that the potential is the work carried out by the charge unit, the work will be 1/2 QV or 6Q joules.

Negative charges move through the wire from low potential to high potential. The "systemic model of potential difference" proposed for the movement of electrons in a wire remains rather simple: they provide a coherent interpretation at microscopic level for the "mechanism" of charging of bodies. Using this model, one needs to separate and relate the concepts of charge and electrical potential (energy) in order to be consistent with the completion of the charging process. This model is used in step C to introduce the definition of electrical capacitance. Homework included many questions asking students to differentiate elements of the model which implied eliciting the pertinent variables of the model by discussing qualities of the different factors within a theory explaining the processes of electrically charging bodies.

During step D of the sequence, we helped students to develop an explanatory theory that predicts an improvement in the charging process's effectiveness. The expected reasoning requires relationships between two bodies (at least one of which is charged) that are close to one another, their electrical influence and the potential variation of the system. We introduced the capacitor and its electrical capacitance. In the following example the task presents a charging process with constant potential due to the presence of a battery.

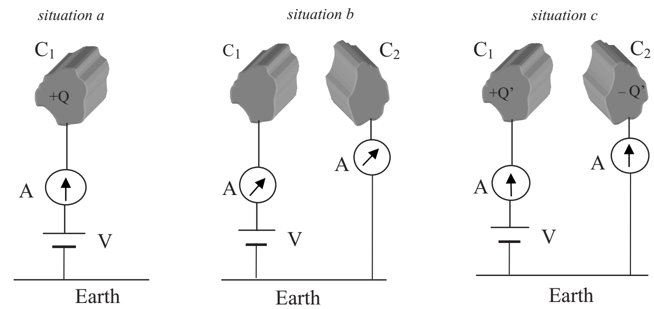
Task. In the diagram, conductor C_1 has been charged +Q by connecting it to the V volt battery (situation a). The ammeter A indicates there is no current. A neutral body C_2 is brought close to it. Conductor C_2 is then grounded and it is observed that the ammeter shows that a current is passing along the wires connected to conductors C_1 and C_2 (situation b), which acquire a final charge $+Q' > +Q$ and $-Q'$ (situation c).

(1) How can you explain this phenomenon? What has happened to the potential of body C_1?

(2) At the end of the process, conductive charge C_2 is now $-Q'$. How do you explain this fact? What is the potential of body C_2?

(3) Has the capacitance of conductor C_1 changed by conductor C_2 being brought close to it?

4. Use the "*Applet_two conductors*" simulation to check and justify your results (url: http://www.sc.ehu.es/sbweb/fisica/elecmagnet/campo_electrico/inducida/inducida.htm#Actividades).



Some students' comments from reports:

> Representative from Group 9: If there is charge movement in situation (b) this is because there is a difference in potential between the battery and the body. This seems to be a contradiction because in situation (a) a balance had already been reached between the potential of body C_1 and the battery. We have assumed that the potential of body C_1 may, in some way, perhaps through electrostatic influence, vary body C_2. There is a potential variation in the system formed by both bodies and therefore a movement of charges in situation b).

> Representative from Group 10: We thought that bringing body C_2 up close would somehow influence the potential of body C_1. In some ways the potential of C_1 has to decrease because otherwise there would be no current movement in situation (b). There is only a movement of charges if there is a difference in potential. We think that by grouping both bodies together we will increase the system capacitance and more charges can be accumulated as Q' is greater than Q.

The examination for this part of the course and the final examination for the course included questions on the difference between the concepts of charge and potential difference (three questions); on understanding a body's electrical capacitance (three questions); and on the concept of a capacitor's electrical capacitance (three questions). Analysis of students' answers is presented below.

IV. ASSESSING THE EFFECTIVENESS OF THE TEACHING SEQUENCE

Students in both the experimental (264) and traditional (182) groups were given qualitative questions designed by the authors (see Appendix). Three paper-and-pencil questionnaires were designed, each with three questions. Some of the items have been discussed in a previous paper on student difficulties concerning Capacitance concept and capacitors [5,21]. The same questionnaires were given over the three years (2005–06, 2006–07, 2007–08).

Regarding the validity of the contents of the questionnaire and its relevance to our goals, four members of our Physics Department, qualified and experienced in physics and physics education, completed the questionnaire and made suggestions that were taken into account when writing its final version. All faculty members confirmed that the contents of the questionnaire were appropriate for any student who had taken the Introductory Physics Course in the Spanish Engineering School, regardless of the didactic strategies used in the course. Additionally, a pilot study was conducted with small samples of students. This confirmed that students generally had no problem understanding the meaning of questions.

We analyzed students' responses to the exam questions from each year and classroom conversations were also recorded (as shown in Sec. III). The recorded conversations were analyzed to assess the reasoning and arguments used by the student work teams when tackling problems. The students' discussions were transcribed literally into a protocol and analyzed on the data interpretation model proposed by Jiménez-Alexandre [29] *et al.*'s interpretation of Toulmin's arguments pattern (TAP) (Toulmin [30]) using frameworks to analyze argumentation that occurs as students engage in decision-making activities in pre- and postvisit sessions. The analysis will help to determine how students use evidence to support explanations and the quality of their argumentation. In accordance with Jiménez-Aleixandre *et al.* [29] we understand argumentation to be the capability to relate data and conclusions, evaluate theoretical ideas from empirical results, draw up reports, etc. (see examples in Sec. III). In this paper, we present the results for the second and third years of implementation because some sections of the second year material were transformed after taking into account experience from the first year. In the second year the number of students in the two experimental classes was 88 (Group E2; 45 Group 1 and 43 Group 2) and 65 students acted as control groups (Group C2, two classes). In the third year, 91 experimental students (Group E3; 44 Group 3 and 47 Group 4) and 56 control students (Group C3, two classes) took part in the study.

All students had previously taken two physics courses involving topics on electromagnetism during post-compulsory education (16–18 years old), and they passed an exam to enter the Engineering School at University. The students were randomly distributed among the first year engineering groups. As stated by Ferguson and Takane [31], the random distribution of students who have undergone the same secondary education is sufficient to ensure the same level of knowledge with the experimental groups. However, to ascertain the students' initial knowledge of electricity and magnetism, we gave sample students from the control and experimental groups the questionnaire entitled BEMA (Brief E&M Assessment) which has been shown to be a reliable assessment tool [32]. The results obtained showed that students' knowledge of the area can be described as memory-based learning of concepts, laws, rules, and procedures, which can be useful for them to solve standard problems and examination exercises, but does not give them sufficient comprehension to apply these concepts to different contexts and phenomena. There were no meaningful differences in correct answers between the eight sample groups form the academic courses 2006–07 and 2007–08 (an ANOVA test of BEMA scores for students at the beginning of the course finds no significant differences for any group). We can therefore conclude that all groups had approximately the same level of academic competence.

Analyzing student answers involved several steps. Using the teaching objectives from Table I as a guide, a preliminary analysis was performed in which the answers were grouped according to the explanations given by students. The criteria that emerged were then discussed in a meeting in which each author analyzed a sample representing 15% of the questionnaires. The original categories were redefined until a consensus was reached. Students' answers were analyzed independently by two researchers, the Kappa Cohen reliability coefficient was 0.83 for the average of the questions corrected, indicating very good concordance in the judges' criteria for setting the categories described. The intrarater reliability Kappa coefficient was also calculated for the main researcher three weeks after, obtaining a value of 0.89, on average for all the questions, which is satisfactory for a level of confidence of 95%.

The answers to all three questionnaires were grouped into the following categories:

(I) Answers that explicitly state the concepts and laws included in the teaching objective for this part of the sequence (correct).

(II) Answers that indicate the main characteristics of the teaching model but do not justify the complete explicative model (incomplete).

(III) Answers in which the concepts are not well applied and/or do not have any further justification (incorrect).

The remaining responses were categorized as either unclassifiable, because the student's responses were unclear, or blank.

The scores for each group's correct answers (categories I and II) were compared. To decide whether there are any significant differences between the experimental and control groups, the statistical chi square is used for the usual level of confidence of 5% or less [33]. The tables group together the experimental and control data for each year, as there are no significant differences between them in accordance with the chi squared statistical results. In the results, the scores correspond to second (groups E2 and C2) and third years (groups E3 and C3).

A. Questionnaire 1: Distinction between charge and electrical potential

From the results of research into physics education, most students analyzed the charging process in terms of the amount of charge which bodies in contact have and did not mention potential difference. Activities in the sequence had been designed so that students built up the meaning of work and energy for these processes. First, how much has the sequence helped to differentiate between the concepts of charge and electrical potential? This part is related to step B (see Table I). To answer this question, we designed the "Charge and potential" questionnaire (see Appendix, Ques-

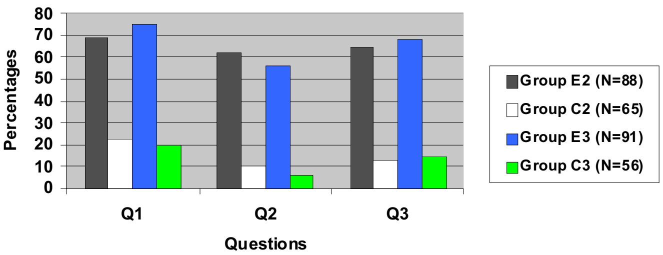


FIG. 1. (Color) Percentages of correct answers regarding differentiation between charge and potential.

tionnaire 1). For example, in question Q3, students had to explain charging spheres in terms of the difference in potential between them and the battery and they have to discuss the work necessary to charge them. An example of this type of answer is given below,

> "The greater charge in the metal sphere is the consequence of that fact that the charges are distributed uniformly in it over the whole surface, whilst on the plastic sphere the charges are concentrated at the contact point, but when they repel each other they cannot spread over the surface which involves greater work because the charges undergo greater repulsion" (question Q3).

In addition, only the nature of each sphere's material could be taken into account if reasoning is in terms of difference in potential. Figure 1 presents the results (category I and II) obtained from the experimental (Second year E2 and third year E3) and control groups (Group C2 and C3). The results indicate that the sequence has a positive effect on using the concept of potential difference to analyze the process of charging a body.

A majority of students in the experimental groups refer to the potential difference concept and many of them reason in terms of the concept of potential and work. In contrast, the vast majority of the control students reasoned in terms of amount of charge tending to become the same in the two contact bodies. This result is similar to the results obtained by Guruswamy *et al.* [8] with North American students. In the case of an insulating body (Q2 and Q3), the majority of experimental students continue using potential difference, but most control students said that the movement of charges was not allowed and therefore there was no charge.

B. Questionnaire 2: About capacitance

We hoped that the students studying the sequence would take into consideration the need for a new concept to measure how difficult or easy it was for a body to be electrically charged. This meant that students would acquire a meaning for the concept of capacitance which is different from the concepts of charge and potential. Some of the questions used to assess this point appear in the "electrical capacitance" questionnaire (Q4, Q5 and Q6) attached and are related to step C (see Table I). The results are shown in Fig. 2.

The vast majority of students in the experimental groups defined capacitance as the degree of ease with which a body stores a charge. Most of the experimental students explained the qualitative meaning of the concept of electrical capacitance (Q5), although there was a significant percentage which only described the formula. If there is a physical meaning to the concept of capacitance, there is no difficulty in admitting that any body, whether it is charged or not, has electrical capacitance. In fact, the majority of the experimental students answered this question correctly (63%), whereas the majority of the students in the control group reasoned incorrectly. The latter students based their answers on the formula and reasoned that if the charge is zero, the coefficient between charge and potential is also zero and there is therefore no capacitance.

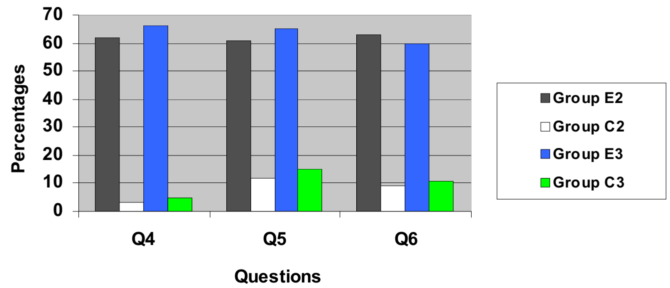


FIG. 2. (Color) Percentages of correct answers on the meaning of capacitance.

The results of questions Q4, Q5, and Q6 were similar and showed that the sequence has influenced students to apply the definition of electrical capacitance with meaning. However, there was a drop in correct reasoning when students analyzed electrical interaction phenomena in dielectrics (question Q2). It will be necessary to look at this point in greater detail in subsequent implementations of the sequences.

C. Questionnaire 3: Electrical influence between close bodies and capacitors

With the aid of the sequence we hope that students will argue by considering the charging process as a system made up of bodies and the medium (systemic model) and not reason on the basis of each isolated body. This means understanding the use of capacitors as suitable apparatus for increasing the effectiveness of the charging process and therefore the capacitance of the system. The results of the questions on these aspects (Q6, Q7, Q8 attached) are shown in Fig. 3.

The electrical influence between adjacent bodies was acknowledged by the vast majority of students who followed the sequence. They recognize that electrical induction influences how much work must be done to bring the same amount of charge to a body. According to this type of reasoning, three quarters of experimental students acknowledged that electrostatic induction is exerted between two adjacent bodies (when at least one of them is charged) causing the potential difference of the system to drop and therefore its capacitance to increase. Examples of this type of answer are given below:

> "The charging process will be easier when there is a

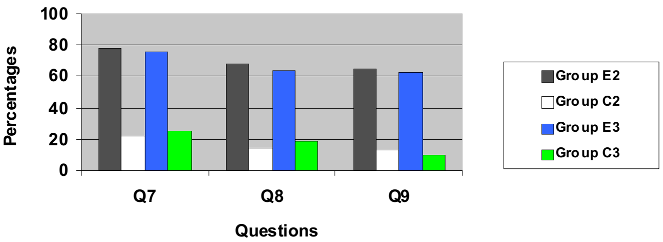


FIG. 3. (Color) Percentages of correct answers on electrical influence and capacitors.

> body A′ with charge −Q′ nearby, as there will be a lower potential difference that makes it easier for positive charges to approach"

> "If we bring the negatively charged conductor close, it will attract the positive charges from A causing the phenomenon of induction. It will be easier to increase its charge, because if we put a + charge between the two conductors, the work done to take this charge to the conductor A will be less, as the negative charges of A′ help and, therefore, less work is done"

Still on Q7, the control group students interpret that the charging process occurs exclusively by electrical contact between the two bodies A and A′ without considering the electrical influence (polarization phenomenon) between two close bodies and the consequences that are derived from the potential difference magnitude.

The percentages in the experimental groups are statistically different from the control group in both 06–07 and 07–08 ($p \ll .01$) in all questions. In the same way, there were no significant differences from one experimental group to another, and likewise for the control group. All statistics were calculated using the statistical chi square under the hypothesis that the treatment would lead to an increase in the conceptual understanding of electrical capacitance in the context of body charging processes.

As Etkina *et al.* [34] propose "in science and engineering education, students have to acquire not only conceptual and qualitative understanding of physics principles but also the science process abilities that are needed to construct explanatory models" (p. 020108–1). The experimental students' answers to the questions show that the majority of students were able to predict the outcomes of the activities based on the data and theoretical model. The teaching sequence gives students the opportunity to acquire scientific abilities.

V. CONCLUSIONS AND IMPLICATIONS FOR TEACHING

The aim of this paper was to design and implement a teaching sequence for the concept of electrical capacitance in phenomena when charging a body. From this perspective, the explanatory model and the comprehensive use of the concepts of capacitance and electric potential is problematic for a significant proportion of students. The approach in the sequence is based on helping students establish connections between the movement of charges (microframe) and an energy analysis of the system (macroframe). Students are helped to construct a model which gives meaning to the concepts of charge, electric potential, and electrical capacitance.

Since implementing the sequence, a considerable number of students have achieved a more satisfactory grasp of the electrical capacitance of bodies and charging processes. This seems to confirm that the aspects highlighted in the sequence are relevant to defined aims; in particular, aspects which explain charging processes in a body including comprehensive connections between charge, electric potential and electrical capacitance; likewise, by carrying out a systemic analysis which takes into account not only the body to be charged but also its surroundings. From this point of reference, the explanatory model provides students with a "non-accumulative vision of charging" the electrical capacitance of a system. The qualitative capacitance of the model gives students a set of ideas which allows them to argue efficiently about charging processes and the electrical capacitance of bodies. This conclusion is consistent with other research showing that students can learn much more about a scientific model by emphasizing fundamental physical principles and, comparing and contrasting its usefulness than by studying the model characteristics alone [34,35].

This study has opened up many questions for further research. In observations of students doing homework, we have found that while many students were able to correctly answer homework questions about electrical capacitance, they seemed not to relate the processes of charging to other electrostatic concepts from previous chapters such as electric potential or electrical field. This provides a sharp contrast to our observations in other parts of the course such as mechanics. For this topic, students were more able to connect kinematic and dynamic concepts and models than electrostatic ones.

We found throughout the course that students did not develop model-building skills to the degree we had hoped. Most students could describe the model, but had trouble making inferences from observations; they often memorized rather than had a clear mental picture of the model. Research by Van Heuvelen [36] and Etkina *et al.* [37] suggests that scientific reasoning skills are difficult to develop without a curriculum specifically aimed at giving students practice in engaging in scientific activity. While several such curricula have been developed for Spanish Secondary Physics education, little work in this area has been done in the field of electromagnetism at university level.

Although this study has not analyzed the implications of extending this type of teaching to other new teachers in the type of strategies that are used in this study, we believe that it could be useful for teaching staff's professional development. However, it should be highlighted that its application by newly qualified teachers should be accompanied by prior training and mentoring [38,39]. In fact, previous work is required between the group of teachers that discuss and take into account the different possibilities that can occur as a result of the activities. Training is also required in terms of designing questions and on how to work with the students. The type of question has to represent a challenge to stimulate reflection and search for solutions on the one hand and, on the other, not exceed the students' cognitive abilities. Balancing this represents a real challenge for the group of teachers that requires taking into account the results of the research into teaching physics and applying them within the context of problem solving.

In response to these problems, more research is needed to determine whether and how designing a global electromagnetism curriculum can be used more effectively to help students practice scientific skills and build explanatory models.

APPENDIX

1. Questionnaire "Charge and electrical potential"

Q1. A metal sphere is connected to another body charged by means of a metal wire. Thus:

(a) The sphere will accept the charge indefinitely until the charge from the other body is exhausted.

(b) A time will come when the sphere will accept no more charge, even though the other body is still charged.

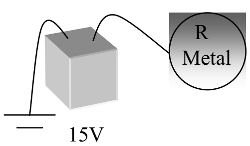
(c) Another possibility.

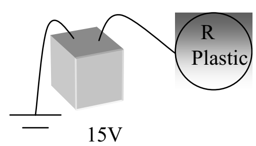
Explanation:

Q2. If the sphere in the previous question were made of wood, would there be any variation in the charging process?

Explanation:

Q3. Two spheres, one metal and the other plastic, with the same radius, R, are connected separately (see diagrams) to a 15-V generator. Which will receive the greatest charge? Why?





2. Questionnaire "Electrical capacitance"

Q4. Consider the same conductor in two different situations:

(a) its net charge is zero. Does this conductor have electrical capacitance?

(b) its net charge is positive +Q. Does this conductor have electrical capacitance?

Q5. Explain what the electrical capacitance of a conductor means to you. Is there any point in speaking about the capacitance of an insulator?

Q6. Consider the same conductor in two different situations:

(a) surrounded by air

(b) submerged in oil

Reason out whether the electrical capacitance of the conductor is greater, less or the same as the capacitance of the conductor in oil.

3. Questionnaire: "Capacitor"

Q7. Let us consider a conductor A with charge +Q. When will it be easier to continue charging it and increase its charge?

(a) When it is insulated

(b) When another conductor A′ charged with +Q′ is brought up close to it

(c) When another conductor A′ neutral is brought up close to it

(d) When another conductor A′ charged with −Q′ is brought up close to it

Q8. Body A has a net positive charge Q and another body B is brought up close to it. Due to the presence of B, will the capacitance of A increase, decrease or remain the same, if:

(a) B has a positive net charge q.

(b) B has a negative net charge q.

(c) B has a zero net charge.

Justify your answers in each case

Q9. It is well known that a cylindrical conductor shell with a radius R_1 has less electrical capacitance than a system made up of the same shell surrounded by another hollow cylindrical conductor with a radius $R_2 > R_1$. What do you think this may be due to?

[1] B. Eylon and U. Ganiel, Macro-micro relationships: the missing link between electrostatics and electrodynamics in student's reasoning, Int. J. Sci. Educ. **12**, 79 (1990).

[2] P. M. Fishbane, S. Gasiorowicz, and S. T. Thornton, *Physics for Scientist and Engineers*, 2nd ed. (Prentice Hall, New Jersey, 1996), for second reference in p. 2, Chap. 26).

[3] P. Mulhall, B. Mckittrick, and R. Gunstone, "A perspective on the resolution of confusions in the teaching of electricity, Res. Sci. Educ. **31**, 575 (2001).

[4] A. Benseghir and J. L. Closset, The electrostatics-electrokinetics transition: historical and educational difficulties, Int. J. Sci. Educ. **18**, 179 (1996).

[5] J. Guisasola, J. L. Zubimendi, J. M. Almudi, and M. Ceberio, "The evolution of the concept of capacitance throughout the development of the electric theory and the understanding of its meaning by University students, Sci. Educ. **11**, 247 (2002).

[6] H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 12th ed. (Addison-Wesley, New York, 2004), Vol 2, Chap. 24.

[7] E. M. Purcell, *Electricity and Magnetism, Berkeley Physics Course*, 2nd ed. (Mc Graw Hill, Inc., Berkeley, 1984), Vol. 2.

[8] D. E. Roller and R. Blum, *Physics, Electricity, Magnetism and Light* (Holden-Day, Inc., San Francisco, 1982), Vol. 2.

[9] L. Viennot, *Reasoning in Physics, the Part of Common Sense* (Kluwer, Dordrecht, Nd, 2001) Chap. 11.

[10] R. W. Chabay and B. A. Sherwood, *Electric & Magnetic Interactions* (John Wiley, New York, 2002), Vol. 2, Chap. 19.

[11] R. Russ, Dissertation thesis, University of Maryland, 2006.

[12] J. Park, I. Kim, M. Kim, and M. Lee, "Analysis of students' processes of confirmation and falsification of their prior ideas about electrostatics," Int. J. Sci. Educ. **23**, 1219 (2001).

[13] C. Furió and J. Guisasola, "Concepciones alternativas y dificultades de aprendizaje en electrostática. Selección de cuestiones elaboradas para su detección y tratamiento," (Alternative conceptions and difficulties in learning Electrostatics. Selection of questions for detection and treatment of them), Ens. Cien. **17**, 441 (1999).
[14] C. Guruswamy, M. D. Somers, and R. G. Hussey, "Students' understanding of the transfer of charge between conductors," Phys. Educ. **32**, 91 (1997).
[15] I. Galili, "Mechanics background influences students´ conceptions in electromagnetism," Int. J. Sci. Educ. **17**, 371 (1995).
[16] C. Furió, J. Guisasola, and J. M. Almudí, "Elementary electrostatic phenomena: Historical hindrances and students' difficulties," Can. J. Sci. Math. Technol. **4**, 291 (2004).
[17] B. A. Thacker, U. Ganiel, and D. Boys, Macroscopic phenomena and microscopic processes: Student understanding of transients in direct current electric circuits, in Physics Education Research, a supplement to Am. J. Phys., **67**, S25 (1999).
[18] D. Psillos, *Teaching introductory electricity, Connecting Research in Physics Education with Teacher Education*, edited by A. Tiberghien, E. L. Jossem, and J. Barojas, International Commission on Physics Education (International Union of Pure and Applied Physics, 1998), Vol. 1.
[19] S. Stocklmayer and D. F. Treagust, "Images of electricity: how do novices and experts model electric current?" Int. J. Sci. Educ. **18**, 163 (1996).
[20] R. P. Feynman, R. B. Leighton, and M. Sands, *Lectures on Physics, Mainly Electromagnetism and matter* (Addison-Wesley, Reading, MA, 1964).
[21] J. Guisasola, J. L. Zubimendi, J. M. Almudí, and M. Ceberio, *Using the Processes of Electrical Charge of Bodies as a Tool in the Assessment of University Students' Learning in Electricity*, edited by R. Pintó and D. Couso, (Springer, Dordrecht, Nd, 2007), pp. 225–236, Contribution from Science Education Research.
[22] J. Park and I. Kim, "Analysis of students' responses to contradictory results obtained by simple observation or controlling variables," Res. Sci. Educ. **28**, 365 (1998).
[23] J. D. Bransford, A. L. Brown, and R. R. Cocking, *How People Learn: Brain, Mind Experience and School* (National Academy Press, Washington, D.C., 1999).
[24] M. Méheut and D. Psillos, "Teaching-learning sequences: aims and tools for science education research," Int. J. Sci. Educ. **26**, 515 (2004).
[25] J. Guisasola, C. Furió, and M. Ceberio, *Science Education Based on Developing Guided Research*, Science Education in Focus, edited by M.V. Thomase (Nova Science Publisher, Ciudad, 2008), pp. 55–85.
[26] M. Dancy M. and C. Henderson, "Framework for articulating instructional practices and conceptions," Phys. Rev. ST Phys. Educ. Res. **3**, 010103 (2007).
[27] Open Course Ware, "Teaching Introductory Electromagnetism for Engineering students" http://ocw.ehu.es/ensenanzas-tecnicas/actividades-para-el-aprendizaje-del-electromagnetismo-en-primer-curso-de-fisica-para-ciencias-e-ingenieria/Course_listing
[28] A. Elby, "Helping physics students learn how to learn," Am. J. Phys. **69**, S54 (2001).
[29] M. P. Jiménez-Aleixandre, A. Bugallo Rodríguez, and R. A. Duschl, "Doing the lesson" or "doing Science:" Argument in High School Genetics, Sci. Educ. **84**, 757 (2000).
[30] S. Toulmin, *The Uses of Argument* (Cambridge University Press, Cambridge, England, 1958).
[31] G. A. Ferguson and Y. Takane, *Statistical Analysis in Psychology and Education* (McGraw-Hill, New York, 1989).
[32] L. Ding, R. W. Chabay, B. A. Sherwood, and R. Beichner, "Evaluating an electricity and magnetism assessment tool: Brief electricity and magnetism assessment," Phys. Rev. ST Phys. Educ. Res. **2**, 010105 (2006).
[33] L. Cohen, L. Manion, and K. Morrison, *Research Methods in Education* (Routledge Taylor and Francis Group, London, 2007).
[34] E. Etkina, A. Karelina, and M. Ruibal-Villasenor, "How long does it take? A study of student acquisition of scientific abilities," Phys. Rev. ST Phys. Educ. Res. **4**, 020108 (2008).
[35] M. A. Kohlmyer, M. D. Caballero, R. Catrambone, R. W. Chabay, L. Ding, M. P. Haugan, M. J. Marr, B. A. Sherwood, and M. F. Schatz, "Tale of two curricula: The performance of 2000 students in introductory electromagnetism," Phys. Rev. ST Phys. Educ. Res. **5**, 020105 (2009).
[36] A. Van Heuvelen, "Learning to think like a physicist: A review of research-based instructional strategies," Am. J. Phys. **59**, 891 (1991).
[37] E. Etkina, A. Van Heuvelen, S. White-Brahmia, D. T. Brookes, M. Gentile, S. Murthy, D. Rosengrant, and A. Warren, "Scientific abilities and their assessment," Phys. Rev. ST Phys. Educ. Res. **2**, 020103 (2006).
[38] L. C. McDermott, "A perspective on teacher preparation in physics and other sciences: The need for special science courses for teachers," Am. J. Phys. **58**, 734 (1990).
[39] E. F. Redish, "Implications of cognitive studies for teaching physics," Am. J. Phys. **62**, 796 (1994).