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Research based teaching sequence of Electromotive Force in the Context of dc Circuits

Guisasola Jenaro[1], Garzón Isabel[2], Zuza Kristina[1]
[1] *Applied Physics Department, University of the Basque Country, Plaza de Europa 1, 20018 San Sebastian, Spain.*
[2] *Department of Physics, National Pedagogical University, Calle 73, N. 11-95 Bogotá, Colombia.*

E-mail: jenaro.guisasola@ehu.es

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Abstract

In this paper, we discuss the impact of Physics Education Research (PER) on the educational practice of teaching physics at university level. This paper presents evidence from different studies to demonstrate the potential positive impact of research into teaching and learning physics on students' understanding of physics. We show the case of teaching the electromotive force concept in dc electrical circuits as an example of the positive influence of PER in designing research-based teaching sequences. Finally, we mention some practical challenges and propose some steps that could be taken to ensure PER growth and productivity.

Keywords: Physics Education research, designing and evaluating teaching sequences, electromotive force, Electricity, research achievements.

Resumen

En este trabajo se discuten los efectos de la Investigación en Enseñanza de la Física (PER) en la docencia a nivel universitario. Este artículo presenta evidencias de diferentes estudios para demostrar que la investigación en la enseñanza y el aprendizaje de la física pueden mejorar sustancialmente la comprensión de la física. Se presenta un caso concreto de la enseñanza del concepto de fuerza electromotriz en un circuito eléctrico de corriente continua como un ejemplo de una secuencia didáctica basada en la Investigación en Enseñanza de la Física. Por último, se proponen algunos problemas prácticos y algunas medidas que podrían adoptarse para asegurar una mejora en la enseñanza.

Palabras clave: Investigación en Enseñanza de la Física, diseño y evaluación de secuencias de enseñanza, fuerza electromotriz, Electricidad, logros de la investigación.

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I. INTRODUCTION

In recent decades a growing number of physicists have taken up the challenge of applying a rigorous approach to physics education research, befitting of traditional physics research, to problems relating to learning and teaching physics. This commitment is widely known as "Physics Education Research" (PER). PER concentrates on understanding and improving how physics is learnt by studying the contents of the physics curriculum and what teachers and students do when teaching and learning in schools. The research field relating to teaching science, and Physics Education in particular, has been well-established for some decades. It attempts to integrate knowledge from different fields of research; such as physics, the psychology of learning, the epistemology of science or the pedagogies of the teaching-learning process [1, 2] in a non-mechanical way. This involves incorporating the results from the different knowledge areas into the common aim of teaching physics.

A number of different studies have had a positive impact on physics teaching and learning. One example is research into student's difficulties in terms of learning physics concepts which resulted in designing new instruments to assess students' knowledge and the effectiveness of teaching. Halloun and Hestanes [3] used the results obtained from an investigation into university students' ideas, within the field of Mechanics, to design the "Force Concept Inventory" formative assessment test. Since its design, there has been an increase in the number of physics programmes and textbooks which pay greater attention to conceptual differences. Recently, in the field of electromagnetism, Maloney *et al.* [4] have developed formative assessment instruments with similar aims.

However, research shows that there is a gap between physics teaching practice and the recommendations made from the research. Introducing innovative curricula and methods creates a variety of problems [5]. One of the problems is that, although a great many share theories of teaching principles developed by researchers, there is often no general agreement on what to do concerning teaching a particular topic. A research-based approach should propose what researchers think is appropriate for teaching. The rationale behind the proposed teaching sequences should lead to a very close examination of teaching goals justified on the basis of the research result and not idiosyncratically or based on the educational programme's tradition. This means that the sequence design is based on empirical research evidence. We do not mean to suggest that research-based design for teaching sequences is the only answer to the problem of changing everyday educational practice. However, explicitly justifying the teaching sequences demonstrating the relationship between the research evidence and the proposals for specific contents might help teaching staff to see the use of implementing the sequence in the classroom.

In this paper we will discuss the rationale behind a teaching sequence on the introduction of the concept of electromotive force (emf) within the context of dc circuits. The rationale behind the sequence is to conduct a very close examination of the precise goals in terms of knowledge acquisition and to identify aspects of the sequence that are consistent with the proposed strategies. We use some PER lines to detect aspects, particularly corresponding to learning goals and activities that are likely to appear on a regular basis in the ordinary practice of teaching. This may be understood as dealing with the following question: “What can be done to help design a research-based sequence on teaching the electromotive force concept in dc circuits?” This question may be posed in a more general way: "How does Physics Education Research help when designing teaching sequences?"

The first step towards answering the question will be to select which of the results from PER would be useful when designing a research-based teaching sequence. The second step will be to realise how nontrivial selected directions are learning indicators and activities, pointing out the relationship between the proposed goals, and global rationale. Finally, there will be a discussion on the efficiency of research-based teaching sequences and their implication for physics teaching.

II. IMPLICATIONS OF P.E.R. WHEN DESIGNING TEACHING SEQUENCES

Lijsen and Klaassen (2004) [6] argue that designing learning sequences requires a complex process of applying the general principles of didactics to specific teaching contexts for teaching the subjects on the curriculum. They point out that this task is not linear but rather a cyclical process with the aim of generating knowledge about teaching and learning, relevant to implementing improved teaching methods in the classroom. This may be understood as the fact that designing teaching sequences is not a mechanical process of transferring pedagogical principles and research results to teaching specific science subjects. On the contrary, teaching sequence design is a creative process which considers not only research but also the classroom culture and the circumstances of both teachers and pupils. We will describe the processes involved in designing teaching sequences below.

Within the University of the Basque Country Physics Education Research Group, we have carried out different research projects over the last ten years, mainly aiming to develop teaching sequences to be implemented in the classroom and subsequently assessed [7, 8, 9]. These sequences deal with specific physics topics, mainly in the field of electromagnetism, at introductory physics and engineering courses at university level. In the studies cited we have used a social constructivist theoretical framework, mentioned in greater detail in other papers [10]. This theoretical framework considers teaching and learning science as a process of acquiring knowledge through familiarisation with the methodologies used by the scientific community. Below, we are going to provide a detailed description of how we use this constructivist perspective to interpret the results and contributions from the research when designing and assessing teaching sequences. To illustrate the design steps, we can give the example of the sequence to introduce the concept of electromotive force in the topic of dc electric currents within the introductory course.

Designing research-based teaching sequences takes into account three kinds of research recommendations: a) Students’ interests, attitudes, values and standards; b) Results of empirical studies on students’ ideas and reasoning; c) Contributions connected to the nature of science and how it is learnt and taught. Although research shows that the emotional and value-related aspects cannot be considered without making a close connection to cognitive processes when students are working on their activities in science classes [11], this recommendation is often “forgotten” in designing sequences. Designing goals and activities that relate aspects of science, technique, society and the environment to each other means supporting a presentation of socially contextualised science that encourages students' interest in the scientific topic being taught. Including activities related to Science-Technology-Society-Environment generates interest among students on the study topics, encouraging them to get involved in the solving task [12]. The second kind of contributions, analysing students' ideas involve not only conceptual aspects but also epistemological and ontological aspects. So, this contribution is connected to the third aspect of the nature of science. In this third aspect, which involves relating the school curriculum to the current theoretical framework of Physics, it is important to stress that taking into account the theoretical framework involves the historical development of the topic to be taught, the difficulties that the scientific community had to overcome and the arguments used to construct new concepts and explanatory models. Working from this epistemological analysis on the scientific content of school curriculum, it is possible to define the teaching-learning aims in a well-founded way [13]. In other words, it is possible to justify choosing these aims based on epistemological evidence of the discipline. As a conclusion, all the above can be organised into Table I.

TABLE I. Use of research evidence to design teaching sequences.

Interests, attitudes, values and standards S-T-S-E Aspects	Epistemological analysis of the school curriculum contents Learning indicators	Students' ideas and reasoning Difficulties in learning
Teaching goals Set out specific problems and aims in a sequence		
Interactive learning environment Teaching strategies		

III. TEACHING SEQUENCE TO INTRODUCE THE CONCEPT OF ELECTROMOTIVE FORCE IN DC CIRCUITS IN INTRODUCTORY PHYSICS COURSES

Interrelated reasons converge when choosing the topic of electromotive force (emf) within the context of Electricity, where little research has been done. Firstly, this notion is included in Secondary School programmes (age 16-18) and first-year engineering and science university courses. Secondly, it is a basic prerequisite for explaining how a direct current circuit works and its technological applications. Moreover, an understanding of everyday technological innovations implies knowledge of how a battery works. Batteries as technological innovations are now so spectacular that we can scarcely conceive society without them: pacemakers, hearing aids, mobile phones, a great number of home appliances, etc.

Regarding students' conceptions, there are several studies on students' understanding of concepts such as potential difference and current intensity in electric circuits. Many are based on the experience of instructors who have pointed out problems with how this material is typically taught [14]. Psillos (1998) [15] 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 modelling 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 have been also some empirical investigations on students' difficulties concerning understanding interpretative models of electrical circuits. Research developed at university level has principally focused on students' understanding of the role played by potential difference and current intensity [16, 17]. PER results may be summarized as follows:

- When analysing the battery in an electric circuit, the majority of students do not distinguish between the empirical level (measurement of electric current and voltaje) and the interpretative level (movement of electrons, potential difference or electric field), and expound their own common-sense reasoning instead.
- Students do not understand the meaning of potential difference. They tend to identify potential difference as a property of the charge and not of the circuit.
- The majority of students do not conceive electromotive force as a non-electrostatic and non-conservative action resulting in the separation of different polarity charges in the battery. They consequently do not distinguish between electromotive force and potential difference.
- It is not clear to students how the property of electromotive force is measured, and they associate also it with a property of electric charges.
- Conceptual confusion and deficient learning of the explanatory model prevent students from being able to value everyday technological applications to their full extent.

From the viewpoint of the Epistemology of Science, the concept of electromotive force is relevant since it appeared in the same historical period that produced the transition from electrostatics to electrokinetics [18]. We shall limit our definitions to the case of stationary direct current circuits within the framework of classical physics; the theoretical framework states that to move charges between two points of a conducting wire, a potential difference must exist between two points on the wire. One way to generate a potential difference is to separate charges with different polarity within a spatial area. In dc circuits, this is done by the battery. In this context of simple electrical circuits, the emf is a property that quantifies the energy delivered to the charge unit by the electrical generator. A series of "non-conservative actions" takes place in the battery, through which energy is delivered to the charge unit and this energy is quantified by means of the property 'electromotive force' [19]. Therefore, it is the "work per charge unit done" to produce and maintain the electrical current which makes it relevant to analysing the movement of charges in a simple dc circuit. Whilst the potential difference measures the work per unit of charge 'used up' by the charges when moving from one point to another in a circuit (work carried out by conservative forces), the emf measures the work carried out by the generator to generate a potential difference by separating charges (work carried out by non-conservative forces) [20].

Working from epistemological analysis on the scientific content of the school curriculum and the theoretical framework of classical physics, it is possible to define the teaching-learning aims in a research based way. The research recommends sequencing the main stages that teacher must work through when designing the teaching programme. When designing sequences we use what are known as "learning indicators" to specify what students should learn on the topic in accordance with the school curriculum. We will present the learning indicators drawn up for teaching the electromotive force concept in the context of dc circuits as shown below:

- Potential difference causes charges to move along the conductor.
- One way to generate potential difference is by separating charges. In the case of a battery this separation is work performed by non-conservative forces.
- The property that measures the work per unit of charge performed by non-conservative forces is called *electromotive force*. Consequently, electromotive force is a property of the battery in the circuit.
- Students will use arguments accompanied by rational justifications based on the theoretical corpus of science and on their own scientific working strategies.
- Knowing how to analyse Science-Technological-Society applications that allow them to contextualise the learned theory.

The principles of social-constructivism that support the design mean that we have to take into account the teaching difficulties, learning indicators and ontological aspects. This creative integration leads to a close analysis of the differences between the learning difficulties and the teaching targets set in the curriculum. This analysis should build bridges between activity design and research work. In this respect we can say that we are using evidence from the empirical research when designing the sequence. Table II shows the teaching sequence.

TABLE II. Topic teaching sequence: "What is the function of the battery in a dc circuit?"

Problem sequence	How science works and what should be learnt	Scientific explanations that should be understood
A. What is the interest for studying electric circuits?	**A.** Science is interested in natural phenomena and their social implications.	**A.** Scientific innovations in daily life and technological applications that should be understood during the topic
B. Why do electrical charges move in a conducting wire? How can a continuous flow of charges be maintained (an electric current at macro level)?	**B.** Become familiar with empirical observations or find out about the phenomena studied. Work on organising the experimental information, making hypotheses and selecting the correct strategies, to get an initial explanatory model.	**B.** Descriptive study of the role of charges in a circuit with batteries. Applying the notions of potential and electrostatic potential different to explain the movement of charges within the context of electrical circuits. Construct a first explanatory model of the battery as the element that maintains the potential difference for continuous movement of charges.
C. How does the battery maintain the potential difference between its terminals? How do we measure the work done per unit of charge by the battery to maintain the potential difference between its terminals?	**C.** Complete the explanatory model and define new concepts.	**C.** The analogy of how a Van der Graaf generator works uses a mechanical model to illustrate the internal workings of a battery. *Define the concept of electromotive force for a battery.* How the work per unit of charge is done to separate electric charges with opposite signs.
D. Where does the energy come from required for electric charges to circulate all around the circuit? How do we quantify the energy transferred or transformed in the different parts of the circuit?	**D.** Work on the proposed model to explain the movement of the charges throughout the circuit. Contrast the proposed model when carrying out the circuit's energy balance. Evaluate the validity of the model and its limitations.	**D**. Extend the explanatory model to the whole circuit. The energy relations are studied qualitatively in the battery and between the battery and the rest of the elements in the circuit. Particular attention is given to the meaning, in terms of relations between physical magnitudes, of expressions such as $I \cdot R$, $I^2 \cdot R$ or $\Delta V^2/R$. Use the explanatory model to tackle the confusion between potential difference and electromotive force.

It is best to think about the teaching aims defined in Table II and presented in the National Standards. The curriculum standards provide information on "what should be taught" generally. On the other hand, teaching aims for the panel that we have defined using the research evidence look in even greater depth at what students should learn and justify why they should do it.

The teaching sequence corresponding to the goals set in Table II was designed for students to learn an explanatory model of the role the battery plays in maintaining the current in a simple circuit. To do this, we have used the "Conveyor belt-Van der Graff Generator" analogy. We have worked from the supposition that the use and utilisation of analogies will allow us to communicate ideas, make hypotheses and construct models on how the circuit works in a context that is not familiar to the student [21]. It should be noted that in the sequence, the "Conveyor belt-Van der Graff Generator" analogy is not conceived as a one-off point in the classroom discussion, but as a recurring element mentioned throughout the different phases of the intervention. The analogy is repeatedly used at different points of the teaching to represent different aspects of the 'target' being studied.

The selected analogy tackles the different aspects of the battery's work from the point of view of the mechanical work done by a conveyor belt that is charged by friction and by generating a potential difference between its base and the metal sphere on the Van der Graff. The sequence activities return repeatedly to the different aspects of the analogy (Van der Graff) and the 'target' (the battery) with the aim of demonstrating that the work carried out (the energy put into play) to separate and transport the charges, that in the case of the Van der Graaf generator give rise to a potential difference, is considered to be similar to what happens inside the battery that also gives rise to a potential difference. Mechanical models are widely used in scientific explanations; the case of the kinetic-molecular theory is a good example of this.

The sequence does not work with the students on the belt's external energy exchanges. Some authors have highlighted this as problematic for the case of explanations with students in subsequent courses as it is necessary to consider the energy exchange between the belt and the external environment to rigorously apply the conservation principle to the whole circuit environment [19]. However, in the case that we are dealing with, criticism regarding energy aspects external to the circuit (circuit without the battery) are not relevant for the explanatory model that we want the students to learn (see Table II) as we only take the electric circuit as the system, without considering its environment.

Working from an understanding of what happens in the battery, we can introduce the concept of electromotive force as the magnitude that measures the work per unit of non conservative charge (mechanical in the Van der Graff and chemical in the battery) required to separate charges. Thanks to this work, we have sufficient energy for the charges to move through the circuit (the potential difference between the poles). This energy balance is used to define the equation for the whole circuit $\varepsilon = \Delta V + Ir$ (Kirchhoff' s Second Law), and the equation for the circuit minus the battery and with resistor R, $\Delta V_{ab} = I R$ (Ohm's law).

Although many of the activities from the innovating educational sequences are common to the questions and exercises from textbooks used in regular teaching, it should be highlighted that they are used differently. Maybe the most significant differences revolve around the time dedicated to student difficulties, plus activities that aim to get the students interested in the topic and justify introducing new models and concepts. The sequence activities are designed with the aim of providing students with opportunities to understand and apply the same model repeatedly. On the other hand, the activities also tackle epistemological aims by getting students to appreciate the power of a scientific model capable of explaining a great number of experimental cases. In conclusion, the aforementioned teaching strategies are not found in regular teaching practice.

In addition, research shows that, given new proposals, teachers are not passive recipients but interpret and select from them. Consequently, teachers may introduce changes when implementing the curriculum, which may affect original intentions, and envisaged goals. This may lead to their teaching veering off track from its “official” goals. Moreover, teachers point out that their educational practice is strongly influenced by their school colleagues and by textbooks and didactic materials used in classroom practice [22]. Consequently, the teaching strategies proposed in our sequences are shared with the teaching staff who will implement the material in discussion seminars and in tutoring sessions throughout the implementation. In addition, the material gives the teaching staff detailed strategies to follow and possible results based on our own teaching practice and the perspectives of the theoretical framework.

Although the sequence design is strongly supported by evidence from research, it is necessary to assess how it is implemented in relation to learning indicators. This means that talking about teaching sequences based on evidence from research involves assessing their implementation. This aspect will be mentioned in the next section.

IV. ASSESSMENT OF TEACHING SEQUENCE AND CONCLUSIONS

Physics education research, generating relevant knowledge about teaching science subjects, presents significant difficulties. Firstly, considering that one proposal is “better” than another involves agreeing with the aims used to assess the quality of the proposal. These quality criteria may be based on the percentage of students who pass official internal and external tests which may have some correlation with the students' results in conceptual comprehension tests.

In other words, quality may be measured in terms of the number of students preparing to following science and engineering studies and in the proper preparation of this elite group. An alternative method of measuring quality revolves around how effective it is at generating better scientific literacy and increasing the wider understanding of basic scientific theories. Finally, the nature of the teaching quality is a question of values, concerning educational administration and, finally, the teachers responsible for implementing it. In any event, if different quality criteria are applied in different situations, it is not possible to identify a single "best teaching practice'.

Teaching sequence implementation is usually assessed in three ways (for more precise details see [7, 8, 9] and [10]). Firstly, we are interested in the effectiveness of the sequence compared to the traditional approach to teaching. Pre-test and post-test analysis is used for this, consisting of a questionnaire with questions related to the learning indicators specified for the sequence. In addition, the students' conceptual understanding in the experimental groups is compared with a Control group. These results are used to judge the sequence's effectiveness in terms of improving the students' understanding, compared to traditional teaching of the subject. We are aware of the methodological difficulties involved in making these kinds of comparisons, but we agree with Leach & Scott (2002) [23] that if they are made in accordance with the conditions imposed by quantitative research methodology, they are at least as valid as any others.

Secondly, a group of tasks is usually used to assess the experimental groups' conceptual and methodological understanding. These tasks are carried out by the experimental group students throughout the sequence implementation. The task structure meant that students had to explain their decisions and their results, as well as predicting how situations would develop following the scientific model studied in class (assessment of epistemological aspects). Student responses are recorded on audio or video for later analysis.

Thirdly, our goals demand that students should be interested in the tasks and acquire greater interest in the scientific content of the subject. We wish to assess the sequence's influence on student activities. To do so, a Likert scale questionnaire was designed scoring from 1 to 10. It consisted of 13 questions divided into three sections on: the contents, the method of working in class and the satisfaction with which the work was done. The students in the experimental groups completed the questionnaire after finishing the course. A teacher who had not taught the sequence supervised questionnaire completion, done anonymously.

Results from the teaching and learning electromotive force concept in dc circuits show that the majority of students (between 50% and 70%) in the experimental groups demonstrate correct understanding of the studied scientific model. It would actually have been surprised if all the students had answered all the questions correctly. This would have meant that all the students had acquired all the knowledge and skills proposed in the indicators. Our, no less idealistic, intention was for the vast majority of student answers to fall within the "correct" and "incomplete" categories and this was achieved by three quarters of the pupils, in all questions. Similarly, the vast majority of the student groups who answered tasks where it was necessary to apply the scientific model they had studied did so correctly. In the case of control group students, the percentage of correct and incomplete replies did not reach 25% in any of the post-test questions.

The experimental group students also showed a (more) positive attitude to the contents of the experimental teaching sequence. Connections with the concepts studied beforehand and the method of working on the contents in the sequence were particularly emphasised.

What evidence do these results contribute to teaching the topics in question? When drawing conclusions and looking at implications for teaching, it is necessary to bear in mind that the teaching sequences designed in the different projects were implemented in two or three groups of students. In addition, teachers who implemented the sequence are experts in the teaching strategies used and have helped to design some aspects of the sequence. So, we cannot present evidence for more general contexts or teachers who have not been trained to use the sequences. However, we have found that similar research on teaching sequences carried out by international groups [24, 25] has also achieved a significant improvement in teaching the specified indicators.

Our projects are not designed to provide conclusive evidence on why students might improve their learning and, in fact, there may be improvements in learning due to other features of the teaching process. However, we think that the existence of a connection between students' learning improvements in the specified indicators and the implementation of these teaching sequences may be a plausible explanation: the sequence and its implementation having been assessed in accordance with the research methodology into science teaching.

The results contributed by our projects show that, for whatsoever reason, students who follow the sequences are capable of obtaining a significantly better understanding of the scientific models proposed in the learning indicators than students who receive traditional teaching. So, teachers who decide to use these sequences in the future seem likely to be able to help their students learn more effectively than with the traditional teaching approach.

Continuing with the design of materials and strategies, as well as their assessment in extensive samples of schools and at different educational levels seems crucial to us, as in research we base ourselves on the fact that if science teaching (physics) were as it should be, it would not be necessary to spending time getting a better understanding of "how", "when" or "why" students learn.

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