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Towards a research program in designing and evaluating teaching materials: An example from dc resistive circuits in introductory physics

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[This paper is part of the Focused Collection on Curriculum Development: Theory into Design.] We argue that teaching learning sequence (TLS) design needs to be further developed through the explicit articulation of methodology, which comprises the theoretical commitments regarding research and how those give rise to methods for design, implementation and assessment. In this study we propose design based research (DBR) as a methodology to conduct systematic and iterative studies of the design and assessment of educational interventions (such as materials and strategies) as solutions to complex problems in educational practice. This methodology does not specify theoretical commitments regarding the nature of learning and how those give rise to teaching strategies, but the articulation of those commitments is expected as part of the justification for decision making in the design process. In order to demonstrate the framework, we present an example of TLS development in the context of introductory electrostatics and dc circuits. We describe the evaluation of the TLS over three years of implementation, addressing both the capacity of the TLS for involving students in learning the topic and the students' learning itself.

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I. INTRODUCTION

Science education has many goals: promoting the development of content understanding, promoting interest in and motivation for further study, cultivating students' appreciation for the role of science and technology in society, etc. Science education research supports these goals by providing fundamental insights into the cognitive, social, and emotional processes involved in learning, and by generating new techniques, strategies, tools and materials for classroom instruction. Among these practical advances are "teaching learning sequences" (TLS) [1].

Starting with empirical studies on students' idea about a series of phenomena and concepts, and constructivist theories of learning, science education research has developed different research-informed approaches to teaching. A significant line of research that originated in the early 1990s [2,3] focuses on the design and evaluation of medium-scale curriculum products covering the teaching and learning of a scientific topic. These works include sequences of teaching activities with the aim of improving the students' learning of specific topics at a small-scale level (for instance, a few teaching sessions) or at a medium-scale level (a whole sequence of lessons on a particular topic) but typically not addressing the large-scale level of a whole program (of one or several academic terms). The literature refers to such teaching activities as teaching learning sequences [1,3]. A distinctive characteristic of the TLS is its dual character that implies both research and development, pointing at a strong link between the teaching and the learning of a particular topic. A TLS can be broadly defined as "both an interventional research activity and a product, like a traditional curriculum unit package, which includes well-researched teaching-learning activities empirically adapted to student reasoning." [3]. Thus, TLS design reflects the interlink between the development of learning tools and environments and the development of theory. This interlinkage is a complex, cyclical process in which general education principles are applied to the teaching of specific topics in specific contexts [4,5]. In each phase there are opportunities for testing conjectures about student learning and for refining those conjectures on the basis of experience, as well as redesigning the TLS proposal accordingly. As a consequence, researchers have elaborated frameworks, to be used by designers, as interfaces between grand theories

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and the needs associated with developing a TLS on specific topics. The frameworks of this kind found in the literature, which have had significant impact, are presented below.

Lijnse's group [6] described a "developmental research approach" for developing sequences on a single topic. They argue that these studies are a kind of "developmental research" involving the interlacing of design, development, and application of a teaching-learning sequence on a specific topic, in a cyclic evolutionary process enlightened by rich research data. In mathematics education, and subsequently in science education, Artigue [7] introduced "didactic engineering," which has three dimensions for designing and validating a TLS: an epistemological analysis of the topic to be taught, analysis of the students' cognitive characteristics, and analysis of the school context. The Physics Education Group at the University of Washington [8,9] has developed a research program that leads to TLSs that they call "tutorials." In this program, research into physics education, curriculum development, and instruction are closely bound in an iterative improvement cycle. Duit [10] proposed the "educational reconstruction" model, which attempts to combine the German tradition of analyzing the curriculum's scientific content with constructivist approaches. This model considers the structure of the scientific concept, analysis of the educational importance of the content, and empirical studies on the progress of student learning and interest. Guisasola *et al.* [11] and Verdú and Martinez-Torregrosa [12] propose a design framework based on "teaching as oriented-research activity" in which content analysis leads to a precise definition of problem-scenarios that students "investigate" to learn the content.

The aforementioned approaches have involved improving existing material by designing teaching activities based on research results. Thus teaching materials are designed based on the results of research and can be evaluated according to them. Most of these approaches share a few common features. They are typically informed by empirical evidence of students' prior conceptions, an epistemological analysis of the target content, theoretical perspectives on learning that are aligned with the cognitive constructivist approach, and the specific educational context. Articles, such as those cited above, typically present evidence of student learning. However, there is less often a discussion of how the considerations above informed the TLS design, implementation, and assessment. Thus there are still significant gaps in this field of study. In particular, many articles on TLS design lack (a) a detailed explanation of the implicit and explicit decisions taken regarding design and implementation; (b) a detailed specification of the teaching strategies, which are often treated implicitly under the label of "active teaching" or "active learning"; (c) a broad assessment procedure (i.e., one that goes beyond the learning achieved); and (d) a detailed description of the iterative process of refinement. The lack of such explicit descriptions makes it difficult for the science education community to interpret the results presented, to propose systematic improvement to the design, and to build on the findings. In short, the lack of detail inhibits progress in both discerning general insights into learning, and to making cumulative progress in teaching.

We argue that TLS design needs to be further developed through explicit articulation of methodology, which comprises the theoretical commitments regarding research and how those give rise to methods for design, implementation, and assessment.

In this study we have used design based research (DBR) methodology to design, implement, and evaluate TLS [13–15]. DBR has a series of common characteristics, which allow systematizing different elements of design and evaluation. In Sec. II, we discuss the components of our implementation of DBR in general terms. Section III presents a detailed example in the context of teaching dc circuits in an introductory course for university students. Thus, in addition to illustrating the model, the paper documents the nature of student thinking about how charge distributions give rise to current electricity as well as effective strategies for helping students bridge microscopic and macroscopic views of this subject.

II. RESEARCH PROGRAM ON TEACHING SEQUENCES

In our program for TLS development, design, implementation, and assessment are intrinsically linked. All aspects are underpinned by both theoretical perspectives and empirical findings. In Sec. II A we discuss the specific theoretical considerations that informed our design of a TLS on dc circuits. In Sec. II B we discuss general principles for design, implementation, and assessment.

A. Theoretical elements underpinning our research framework

The components of theory that underpin our approach are derived from cognitive psychology (especially socio-constructivism), the epistemology of physics, and physics education research.

In science education research two main perspectives of psychological theory on teaching have been used as a theoretical reference. The first one has its origins in Piaget's genetic epistemology and his ideas on cognitive science [16]. According to this perspective, students' comprehension of scientific knowledge is achieved through a change in the ideas they held previous to instruction. Thus to predict how students will react to the teaching of science, it is essential to understand the previous knowledge that the students bring to a particular learning situation [17,18]. There are several current ideas about conceptual change that have their origin in Piaget's genetic epistemology. Some of these theories are centered on describing students' "mental structures," while others deal with the mechanisms that foster the changes in the individuals' mental structures. [19,20]. These perspectives of learning focused, mainly, on the changes of individuals' mental structures have been complemented by a description of individuals' learning when working in a social context [21]. This interest in the social contexts of teaching and learning has brought into science education research a second perspective of psychological theory with its roots in Vygotskian psychology. The learning and construction of knowledge are seen by Vygotskian, and neo-Vygotskian theories, as originating in the social interactions between individuals through the mediation of culturally generated tools, for instance, language and books. This perspective is at the basis of the social-constructivist perspective of learning. [22]. A fundamental assumption of this cognitive theory is that cognition is not located solely in the individual's mind but that it is primarily a process distributed among the learner, the environment in which the learning takes place, including other participants, and the activity in which the learning takes place. This is one of the theoretical elements underpinning our work, as we will show later, influencing some of the didactic tools we use for the design of the TLS. Specifically, students' previous knowledge is taken into account and particular experimental designs have been designed to probe the students' knowledge and reasoning in relation to the defined learning aims [23]. Additionally, Vygotsky's idea of a "zone of proximal development" where learning can take place is at the core of one of the chosen design tools: "learning demands" [24] (see Appendix A).

Another of the theoretical elements taken into consideration in this work is the history and philosophy of science (HPS). There is a consensus in the literature on the fact that the understanding of the concepts and laws of a particular topic require not only the knowledge of their meaning but also knowledge on how knowledge is acquired and refined through time [25,26]. The structure of science, the nature of the scientific method and the validation of scientific judgements are some of the areas in which HPS can make a contribution to science education [27]. Scientific concepts and theories do not appear miraculously; they are the result of an arduous problem-solving process and the rigorous contrast with an initial hypothesis [28]. Consequently, in this study we have assumed that knowledge about the development of the explanatory ideas that resulted eventually in the present scientific model can provide important information to help researchers better understand the meaning of a topic and its role in physics, supporting the construction of relevant learning aims and teaching strategies. In our study this has entailed, first, to research the primary and secondary historical and philosophical sources related to the production of electric current and electric circuits [29]. This research provided arguments to justify the key ideas that would become the learning objectives of the TLS "foundation of dc circuits" (see Sec. III A 2). Second, knowledge of the development of the explanatory ideas, which finally evolved into the present scientific model, can provide important information when determining where are the fundamental problems related to the construction of the concepts and theories of the topic to be taught. This shows the epistemological and ontological barriers that had to be overcome and the ideas that fostered progress.

The inputs from HPS do not necessary imply a sequence of activities guided by the historical development of the topic. The sequence should actually avoid presenting the past as a lineal antecedent of the present or oversimplified versions of the nature of scientific research [30]. In our study, as it can be seen in Sec. III A 2, the insights from HPS have been used to justify epistemologically the aims of the teaching of the topic for the chosen educational level and to define the "driving problems" which are posed to the students with the intention of helping them acquire a preliminary ideas of the tasks to be carried out to achieve the learning aims.

This work has also taken into account the literature on physics education research (PER) [31]. We have carried out a PER literature review on the students' difficulties when learning electric circuits at introductory physics level [32,33], and different teaching approaches have been revised, from traditional programs to innovative proposals. For this work we have taken into account the indications given by the new standards that stress the integration of scientific concepts and practices [34,35]. However, facilitating students' work, which emphasizes the integration of scientific practices with the content, is a complex matter. To address this problem, the structure of the activities follows the recommendation of the literature on problem solving in physics and that on the work with small groups in the classroom [36,37]. As it can be seen in the examples from the activities (see Sec. III B 1, Fig. 1 and Fig. 2) students are presented with "situations" and, by posing some questions, they are given opportunities to use evidence to solve problems and use epistemic practice to communicate their ideas. Taking part in scientific practices requires students to participate in the classroom science discourse [38,39]. The traditional roles of authority and novice are blurred, as students work in cooperative teams solving problems that have already been solved (as opposed to novel investigations) under the direction of a teacher who knows the solution well. It is a process similar to the initial training of future researchers and for this reason we call this teaching strategy "teaching as oriented research activity" [40].

The relationships established in this work between the theoretical elements and the didactical tools to design and assess the TLS are systematized through a DBR methodology presented in Sec. II B. Furthermore, these relationships are not established mechanically but are guided by the pedagogical content knowledge, and the professional experience of the authors and their research groups.

Therefore, this work is indebted and is based upon previous work carried out in the research groups of which the authors have been part (see, for example, Refs. [41–47]).

B. The "design based research" methodology for developing teaching learning sequences

As we have mentioned before, we wanted to use a methodology for the design and evaluation of a TLS that could help the science education community to have a common tool to address the existing gaps that prevent TLS design from becoming a research program. We argue that DBR is a good candidate for such a methodology. In this section we will briefly explain the methodology, how it has been used in educational research so far, why we think it can help bridge the gaps we have identified in TLS design, and how we have implemented it.

Design based research methodology has been used in education and the learning sciences at least since 1992 [48,49]. DBR has been applied by educational researchers to a wide range of education innovations (such as teaching tools, learning activities, designing scaffolding), school contexts and curricula. Among the research that has used DBR, different approaches and methodological tools have been implemented. This has led to criticism about the lack of methodological rigor of some investigations using DBR [50], the need to set clear quality standards and the need for a wider range of research tools for the evaluation phase [51]. But, notwithstanding these criticisms, DBR has been adopted by a very considerable number of researchers [52] and they have been shown to produce fruitful results in different areas and, in particular, in the production of instructional solutions [50]. There are different takes on how to define DBR methodology but most authors agree that it is a cyclical process that typically comprises three phases: design, implementation, and assessment [53]. The methodology does not assume a particular underpinning educational theory or specific tools for any phase, thus giving educational researchers considerable latitude on how to implement DBR [15]. As a methodology, DBR has been shown to have the potential to bridge the gap between educational practice and theory, because it aims to both develop theories about domain-specific learning and the educational materials that are designed to support this learning [54]. Hence, beyond its focus on producing educational innovations to be implemented, DBR has been proven fruitful at generating causal reports on learning and instruction, which is needed to have research-based science education [55].

So far we have seen that DBR is a methodology that already has been established in education for research that aims at producing educational materials. Furthermore, the literature indicates that it can improve the explicit connection between the theoretical foundation and the design of research-based TLSs and to address the other gaps we have identified in TLSs research. DBR has the potential to clarify those aspects that have been indicated as improvable in the investigation of TLS designs. In particular, in this work we focus on (i) more explicit explanations about the decisions taken regarding design and implementation, (ii) more detailed explanations of the teaching strategies used in the TLS materials, and (iii) a broad assessment procedure with a detailed description of the iterative process of refinement [13].

In the following section we will present how we have interpreted each of the phases of DBR and the specific choices we have made to take into account the theoretical elements and research results presented in Sec. II A. For the sake of brevity our explanation might seem quite linear, but we have, in our work, adhered to the idea that a DBR project in education must take into account that the design aims and the learning theories underpinning the proposal are interwoven and that the project must develop through cycles of design, implementation, analysis, and redesign [56]. We have also tried to report on how our research has paid attention to both the learning results and the interactions during implementation that can provide new insights on our understanding on the learning problems involved [57].

1. Design phase

The design phase explicitly connects relevant theory with the design of the instructional intervention. This phase leads to an initial product (in our case, a TLS) that includes a hypothetical learning path consistent with the theory. This phase starts with an evaluation of the learning goals for the target audience. As DBR takes place in naturalistic contexts, we identify most of the contextual elements (curriculum, educational level, audience, etc.) that will limit the scope of the TLS. TLS design includes also structured activities and hypotheses about students' potential learning processes and guidance on how the teacher can support these processes. In this design phase, according to the theoretical elements that we have defined (Sec. II A), we establish in our TLS design two design tools. We use the term "design tools," in the same way as Ametller, Leach, and Scott [42], to highlight that the theoretical and empirical insights are explicitly and intentionally used in making design decisions. We have used two design tools—epistemological analysis and learning demand—that we explain briefly in Appendix A.

2. Teaching experiments

Classroom implementation of the TLS aims to investigate the hypothesis that the design will lead to improved student performance, as judged by predetermined assessment strategies. This phase can be considered a "teaching experiment". As Cobb *et al.* [57] state, "a primary goal for a design experiment is to improve the initial design by testing and revising conjectures as informed by ongoing analysis of both the students' reasoning and the learning environment."

Taking into account the contributions of the PER literature that we mentioned in Sec. II A, and the objective of explaining in detail the teaching strategies that are used during implementation of the TLS in class, the TLS serves as a guide for the teacher on what and how to teach, how to interact with students, and how to observe the process.

The teacher might feel the need to make adjustments in the TLS as students' progress. These changes might be due to incidents in the classroom, such as students taking approaches that had not been envisioned, activities that are too difficult, etc. These adjustments are generally not accepted in comparative experimental research, but in DBR, changes are made to the TLS to create optimum conditions and they are considered elements of the body of data. This means that these changes should be well informed and backed by theoretical considerations. These aspects should be taken into account in the TLS assessment instruments as we mention below.

The specific characteristics of the implementation in class are described in Sec. III A 1.

3. Evaluation: tools and refinement

In the evaluation phase, the initial TLS is empirically tested. However, the DBR methodology does not define the research tools that should be used. These tools should be chosen by the researchers in accordance with the aspects being evaluated. In our program, we propose retrospective analysis of the implementation in two dimensions that include a broad assessment that usually is not explicit in most of TLS designs [58]:

(a) Analysis of the quality of the sequence, which involves (a.1) problems related to the clarity of the activities to be carried out by students, (a.2) problems related to the time needed to complete the sequence, and (a.3) unanticipated problems inherent in writing a new sequence with innovative content.
(b) Analysis of learning outcomes, which includes students' (b.1) understanding of the concepts, theories, and models; and (b.2) acquisition of scientific skills.

For the first dimension of retrospective analysis of the TLS, we use a qualitative research methodology with tools such as the "teacher diary" [59], the "student workbook" and the "external evaluators report," which is a classroom observation report filled out by a member of the research team, focusing on whether the teacher follows the aims of the TLS activities. These tools are used as a source of data and to analyze if the aims of the activities are perceived by the teachers as they were intended by the designers, as well as to detect the difficulties encountered in implementing a sequence with innovative content. We use qualitative research tools here because our study is exploratory in nature. Our aim is not to obtain generalizable results on the effectiveness of the designed TLS but to ascertain whether the proposed methodology (DBR) is helpful for overcoming some of the identified difficulties of the design and redesign of TLSs.

In the second dimension of the analysis of learning, we use quantitative research tools such as questionnaires with open-ended questions to assess students' understanding of concepts and theories (pre- and postquestionnaires for both the control and experimental groups), and tests including problems that assess the learning of laws and the acquisition of science skills (post-test for the experimental group only).

On the basis of the data, we infer problematic aspects of the activities. Following this analysis, we identify types of student difficulties (metacognitive difficulties, reasoning difficulties, difficulties related to interpretation and comprehension of information, etc.) and we proceed to introduce modifications to the activities and their sequencing. The analysis of the data allows us to redesign the TLS according to the two dimensions we intend to evaluate. Particularly, the results of the evaluation can influence aspects of the redesign of TLS such as rewriting parts of the text, modifying the analogies used, and the general approach of the TLS; the re-sequencing of activities; the redesign of images and figures; restating prerequisites for the sequence; modifying the format (worksheets, classroom response system, etc.). The analysis of the results provides designers with feedback on the validity of the TLS and its theoretical assumptions. This improves the probability of finding an effective design that can be verified afterwards through the final evaluation.

In the following section, we illustrate this research program for the case of the "basic electrical circuits" topic in an introductory university physics course.

III. DESIGNING AND EVALUATING A TLS FOR THE TOPIC OF dc CIRCUITS IN THE CONTEXT OF INTRODUCTORY UNIVERSITY PHYSICS

In this section we start by presenting the context for which the TLS is designed (A.1). Then we discuss the epistemological and educational arguments concerning the chosen topic (A.2). The learning goals we developed and the gap between these goals and the students' difficulties are described in A.3 followed by a description of the resulting learning path and learning activities in A.4.

A. Design phase (from learning objectives to a sequence of activities)

1. Educational context

Our TLS on circuits was designed for a transformed calculus-based physics course for first-year engineering and science students at the University of the Basque Country (UPV-EHU). At UPV-EHU, electromagnetism is taught during the spring semester with an enrolment of 60–70 students. The traditional course format is 2 h per week of lectures, and 1.5 h per week of problem sessions. In the electromagnetism course, electric current and direct current circuits are taught for two weeks. The lectures and problem-solving sessions cover current and the motion of charges, resistance, batteries and Ohm's law, combinations of resistors, Kirchhoff's rules, and *RC* circuits. Instruction also covers the use of Kirchhoff's rules to calculate the energy balance in a circuit, and examples similar to those appearing in standard textbooks are given [60]. Situations in which it is useful to consider the energy supplied by the battery and the energy consumed by resistors are shown and analyzed. In the traditional courses, students do not normally have the opportunity to participate actively and are limited to taking notes from the teacher's explanations, both in lectures and in problem sessions. In the transformed version, we adopt the same syllabus (i.e., we cover the same factual knowledge) but, as we will explain, the course and contents are organized differently.

Students who take the introductory physics courses at the UPV-EHU have previously taken three semesters of physics in high school (16–18 years old) (mechanics, electromagnetism, and modern physics) plus they have had to pass the University entrance exam. This implies that the students already have basic knowledge on dc circuits. Moreover, the Conceptual Survey of Electricity and Magnetism test [33], which students take at the start of the semester, shows that they have good declarative knowledge, for example, they perform well on Q6 and Q12. However, they do not apply the fundamental concepts in an appropriate way (for example, they do not perform well on Q15 and Q31). The results show that student knowledge is reasonably uniform.

2. Epistemological insights

The vast majority of textbooks for introductory university physics use the Drude model, which explains that the current in a wire is caused by a potential difference between two points on the wire and that the electrons are guided by an electric field located within the wire, parallel to it at any point [61,62]. The model supposes prerequisite knowledge of the electrical nature of the material and an understanding of the concepts of field and electrical potential, studied previously in electrostatics. The Drude model is sufficient to give an explanation that matches the empirical data obtained by the ammeter and the voltmeter when taking measurements in the circuit.

However, if we look at the traditional treatment of simple electric circuits in textbooks, we can criticize at least three aspects. First, the system itself is not emphasized enough, although it is essential for a deeper understanding of, for example, the relationships between potential difference and the electric current in a wire [63,64]. Second, any connection between potential difference and surface charges, which always exists, is left out, and as a result, introducing potential difference as energy per unit charge is unnecessarily abstract. Last, there is no mention of the transient processes that occur because the approach is based on Ohm's law and Kirchhoff's rules, which are exclusively based on stationary states. In addition, in discussions of the Drude model, it is said that the electrons in a wire are influenced by an electric field within the conductor. In the context of electrostatics, the students have seen arguments that conclude that there is no electric field inside a conductor, and so the previous statement may be puzzling for them. For a physicist, it is evident that the argument does not apply to the dc circuit, as it is in electrostatic equilibrium while the wire is in a stationary nonequilibrium state. However, we have to be aware of the teaching problems involved in working on the transition, from the electrostatic to the dc case with respect to the Drude model.

The aforementioned issues go beyond justifying empirical measurements in dc circuits using meters. At a university or college introductory physics course level, there is often a need to find an alternative to a purely macroscopic description. At the macroscopic scale, we are often left with limited explanations to indicate what the laws predict. These types of explanations are insufficient to satisfy students, especially when alternative conceptions arise. There has been a growing consensus that students benefit from being exposed to the microlevel phenomena that govern electricity and dc circuits [65,66]. It is necessary to justify *how* the electrical field is generated inside the conducting wire and the relation between this electric field and the electric field inside a conductor in electrostatics. In addition, it is necessary to clarify that the relation established in electrostatics ($\vec{E} = -\vec{\nabla} V$) is also valid in an electrical circuit. Regarding the macroscopic and microscopic levels of circuit analysis, it is necessary to relate the potential differences that quantify the energy conservation principle in the circuit (Kirchhoff's second rule) to the electric field inside the wire (the microscopic model of electric current).

The historical development of explanatory models for electric circuits informs the above discussion. The epistemological changes in reasoning and axiological changes with regard to goals and interests adopted by the scientific community can help us define learning objectives. The historical development of the physics of electricity shows that the different steps of developing models are heading towards the unification of electrostatics and electrodynamics into one explicative model. In 1827, Ohm contributed to circuit theory through his law for conductors. Ohm clarified the separate and complementary roles of current and potential at a time when both were confused [67,68]. Kirchhoff made the greatest step in developing the concept of potential and circuit theory by proposing the existence of a gradient of charges on the surface. Kirchhoff demonstrated that Volta's "electrical tension" and Poisson's potential function were numerically identical in a conductor

TABLE I. Epistemological justification of learning objectives for TLS on foundations of dc circuits.

Epistemology of physics issue	Learning objectives
In the history of physics, explanations of the electrostatic and electrical current phenomena were not always integrated in a single model. Since Kirchhoff's work, the physics community has assumed that the basic concepts of electricity are the same for electrostatics and electrodynamics.	O1.- The students recognize that the concepts of electrical field and potential difference are the same in electrostatics and electrodynamics.
The explanations for electric current as a movement of charges (electrons) within a conducting wire represented major progress in the atomic model of matter in the late 19th century.	O2.- The students know how to apply the atomic model of the material to explain and quantify the current of electrons in a conductor for a simple dc circuit, using the voltage gradient between two points on a circuit at macroscopic level.
The papers by Kirchhoff and Weber demonstrated the surface charge density gradient mechanism in the wire to explain why the electrical field is generated inside a wire through which current passes and how it relates to the potential difference.	O3.- The students are able to explain how a surface charge density gradient on the wire produces the electrical field inside the wire and that it in turn produces the movement of electrons (microscopic level). In addition, they are able to relate the electric field to the potential difference throughout the entire circuit.
The contemporary electrical theory sets relationships between the concepts that can be measured with a meter at a macroscopic level (current and voltage) and the explanatory concepts at a microscopic level (field and electrical potential).	O4.- The students know how to relate quantities defined at a macroscopic level and at a microscopic level.

and therefore could be reduced to a single concept. Thus, he showed that electrostatic and circuit phenomena belonged to one science, not two [69]. From this unification, the role of potential came to dominate circuit analysis with little emphasis on surface charge distribution. In 1852, Wilhelm Weber pointed out that although a current-carrying conductor is neutral overall, it carries charges of different density on its surface and a potential difference between two points within an electric circuit is related to a difference in surface charge densities [29]. Sommerfeld [70] discussed the origin of the electric field inside a long straight wire and found that the field inside is generated by charges that are located at the surface of the wire (surface charges).

Several authors have discussed various aspects of surface charges over the years. The experimental aspect has been covered by Jefimenko [71], Jackson [72], Heald [73], Hernandez and Assis [74], and Müller [75], all of whom found analytical solutions for several simple geometries. Hartel [76] took a qualitative approach to more complex geometries, including conductors with varying diameter and resistance. Moreover, Galili and Goibargh [77], Harbola [78], and Davis and Kaplan [79] discussed the role of surface charges in transporting energy from the battery to a resistor, and Preyer [80] carried out numerical simulations to determine the distribution of surface charges.

From the educational point of view, the epistemological analysis of the controversy that led to an electrodynamic interpretation of electric circuits, beginning with Volta's explanation, and continuing with contributions from Ohm, Kirchhof, Weber and Sommerfield, cannot be underestimated [68,69]. The justification of introducing the "gradient surface charge" model into curriculum teaching with the aim, among others, of relating the concepts of electrostatics and electrodynamics, is relevant as it corresponds to the period in the history of electricity when the transition took place between electrostatics and electrodynamics.

In accordance with DBR methodology, we consider the topic and contents defined in the official curriculum for the unit on foundations of dc circuits (context) and use contributions from the epistemology of science to justify and define the learning objectives that appear in Table I.

3. Students' difficulties and "learning demands"

To progress from the defined learning objectives to propose learning activities, we take into account the gap between students' ideas and those learning objectives. The magnitude of the gap they need to bridge to achieve meaningful learning will influence the strategies to be used in each case. In the design of our TLS, we do not take into account all possible student difficulties on the topic of dc circuits, only those related to the defined objectives.

As part of our project we reviewed studies on students' learning difficulties on the topic of electric circuits in introductory physics courses. There are many studies related to objective 2 (a macroscopic model of how an electric circuit works) at the secondary level (12–18 years old) and some at the university level [1,61,29,81]. The research shows that students have a confused understanding of the concept of potential difference, which they only use as a calculation convenience. Most students think that potential difference is a *consequence* of the flow of charges rather than its cause. Often students do not relate macroscopic phenomena (electrical attractions and repulsions, electrical current, battery voltage…) with microscopic concepts, which build the explanatory theory (field, gradient of charges, polarization…) [46,82–84]. However, very few papers have looked at student ideas related to objectives 1, 3, and 4. Consequently, we perceived a need for an empirical study that allows us to establish whether the gap between students' ideas and the defined indicators is significant. Once the learning objectives have been defined, we use the "learning demand design tool" [24], to analyze the ontological and epistemic differences between the students' ideas found in the research and the defined learning objectives. This characterization of the expected difficulties guided the design of the appropriate activities in terms of types of activity, time given allocated to them and the organisation of the work to be done by students, among others.

We conducted an experimental study of students' difficulties when attempting to apply electric field and potential concepts to explain dc resistive circuits [23]. The results show that the majority of the students experience difficulty applying the concepts of electric field and potential difference in electrodynamics by using the same definitions that have been studied in electrostatics. These results are consistent with the difficulty that students encounter in explaining electric current with the "gradient surface charge" model. In short, students have significant difficulty applying the definitions used in electrostatics, as they are situated at a microscopic level. However, most students correctly explain how a circuit works macroscopically using the concepts of potential difference and current included in Kirchhoff's laws. It should be mentioned that this understanding of the laws for a circuit at a macroscopic level is typically better than that reported in other research on the same topic at the secondary level [82,83]. We have not investigated more complex circuits, where university students usually have problems even at the macroscopic level [54]. Students' difficulties with the concepts of field and electrical potential microscopically are demonstrated when they have to analyze the same phenomenon from two points of view: macroscopic and microscopic. Less than 10% of students are capable of explaining the relationships between the macro and micro models for a simple electric circuit.

The previous study [23] demonstrated that new curricular proposals based on a gradient surface charge microscopic model require an elaborate mechanism with underlying multilevel, relational reasoning. Our study shows aspects, barely mentioned in education research at the university level, of the types of reasoning used by students when establishing macro-micro relations and possible difficulties with the multilevel reasoning processes. We suspect, therefore, that not only should an up-to-date curriculum be based on a gradient surface charge model, but it should also provide information on the specific difficulties that the students might encounter when pursuing the defined learning objectives. Within the DBR methodology, this aspect can be addressed by the "learning demands didactical tool," which allows us to evaluate the gap between the learning objectives defined in the TLS and students' ideas. Previous research about students' ideas and our empirical previous study tell us that students' have some difficulties in learning the fundamentals of dc circuits; below we describe the principal ones:

D.1. To apply the concepts of electric field and potential difference in electrodynamics contexts [82,83].
D.2. To apply Kirchhoff's laws to simple resistive dc circuits [82,84].
D.3. To analyze current at the microscopic level, using the concepts of field and electric potential difference [23,84].
D.4. To analyze the circuit from two different points of view: macro and micro [23,81].

Literature shows that the epistemic and ontological differences between the learning objective and students' ideas are big and so the learning demand is high.

4. Designing TLS materials

Taking into account the process described so far, we designed a series of tasks (questions and problems) that should, in principle, help students achieve the learning objectives. The development sequence includes two phases that are integrated iteratively: (a) Sequencing the content; (b) specifying strategies and activities to help learning. Regarding the learning path, it is structured into three driving problems, which are stated as follows:

- *How does electric current work? Macro and micro aspects in an electrical circuit.*
- *What is the mechanism that produces the current and the movement of electrons?*
- *What is the role of the battery in relation to the electric field in the wire?*

These three driving problems structured an initial version of the TLS (henceforth TLS1) during the 2015–2016 academic year with the following order of content presentation: (I) Movement of electrons in a conducting wire: electron current and conventional current; (II) drift velocity; (III) the model of gradient of surface charge; (IV) application of the gradient surface charge model in the context of initial transient current and stationary state current; (V) the role of the battery in a dc circuit; (VI) analysis of simple resistive dc circuits from both macroscopic and microscopic models.

B. Evaluation and refinement of the TLS

This section presents and discusses the assessment and consequent refinement of the TLS. First, we present the preliminary evaluation whose empirical evidence guided refinement of TLS1. Second, we present the results from implementing the refined TLS in relation to the learning achieved. As mentioned earlier, there are two dimensions of the TLS evaluation: (a) analysis of the sequence quality, (b) measurement of the learning achieved by students.

Our evaluation includes qualitative and quantitative tools, not primarily to triangulate the results, but to obtain complementary information on how to redesign the TLS. The reason behind this mixed methods evaluation is the aim to assess the quality of the TLS not just through the learning results from students' tests but also through the evaluation of the implementation of the TLS in classroom situations. Some of the results obtained with different tools concur and, hence, strengthen the decision to change a part of the TLS. Other results, obtained with a particular tool, will point at issues that need to be addressed that will not be addressed by other evaluation tools. The final decisions on the redesign of the TLS must take into consideration all of those results since individual design decisions might impact on more than one issue raised by the assessment process.

For the sake of brevity and to show as clearly as possible how specific aspects of the assessment impact on the redesign we have chosen to focus first on the qualitative assessment and some of its impact on redesign (B.1.) and later on the quantitative analysis regarding students' learning (B.2). Both sections show aspects of how the decision to redesign elements of the TLS1 were reached. Of course, as we have explained before, while the assessment shows which parts of the TLS and its implementation should be improved, the concrete changes in TLS1 to obtain TLS2 come from a mixture of PER results and professional content knowledge (see Table II).

1. Results of the first version and consequent refinement

The first version of the TLS (TLS1) was piloted during the second semester of the 2015–2016 academic year. It was implemented by one of the authors in her class. The time available within the study plan for the fundamental of dc circuits topic is 4 h for theory and 1.5 h for problems. So the activities for our TLS were limited to 5.5 h. In agreement with the teaching strategies based on the theoretical inputs presented in Sec. II A, students' work in the classroom is an "oriented research activity." The teacher provides theoretical information when summarizing the activities' conclusions and shows students where in the textbook they can find the relevant information and examples. In the first implementation (and the subsequent implementations), there were no problems with the available time, although the distribution of activity duration varied from the first implementation to the second and third, due to modifications in the type of activities.

Analysis of the information included by the professor in her "teacher's diary" and the students' workbooks clearly shows that students do not understand the need for a new microscopic explanatory model. It seems that they apply the new model, required by the activity that they have to resolve, but when they can choose an explanatory model, they tend to use only the macroscopic model studied in previous years. For example, in A.3. of TLS1, the teacher wrote in their diary:

> *"In activity A.3: In a copper wire, the current of electrons is about* $i = 3.4 \times 10^{18}$ electrons/s. *This is a huge number of electrons passing through a section of the wire every second. But, how long does it take for an electron to travel a metre along a copper wire?*
> *Make a prediction: a)* 10^{6} seconds*; b) 1 second; c)* 10^{-6} seconds*; d) Something else.*
> *The vast majority of the students write in their workbook that the speed is very high (option a) because the light bulb comes on immediately when the switch is closed. Only when they have to calculate the speed of the electron in the following activity A.4 do they start to think on a microscopic level in the network of electrons and the collisions between them, as well as in the difference between the movement of an electron and the movement of the conventional current."*

The comments in the teacher's diary are focused on the fact that the activities should drive the discussion, as the students are focused on solving it numerically. The activity sequences were reformulated, and a worksheet was added for the next implementation. (see Fig. 1).

The students demonstrate persistent difficulties in differentiating between the surface charges that are generating the field and the moving charges from the cable that form the current. For example, it was necessary to reformulate A.7 so that the students could think about the nature of the charges that produce the electric field inside the wire (metacognitive activity). A.7 was rewritten and a complementary activity was added in the context of a circuit (A.8) (see Fig. 2).

There were no activities with the aim of relating macro and micro perspectives; it was supposed that students would make the connection. However, the results of the activities in the student's workbooks, the teacher's diary notes, and the learning results achieved (see Sec. III B 2) indicated that the students had difficulties in making the macro-micro connection. The need for activities like A.15 was required due to the difficulty bridging both perspectives (see Fig. 3).

In the student workbook, the vast majority performed a correct sequence to explain how the conventional current works at the macroscopic level, but they did not comment on the mechanism at a microscopic level, or they do so

TABLE II. The first column shows the sequence of problems, which, as they are solved, tackle the necessary knowledge for teaching and learning the TLS. The second column shows the learning objectives and the third column explains the strategies to help learning (scaffolding). The fourth and fifth columns list the activities and how they relate to the skills to be worked on for TLS1 and TLS2. Each row presents the learning objectives and teaching strategies connected to each driving problem as well as the activities proposed to address them in the TLSs. O.1 to O.4 refer to the learning objectives defined in Table I.

Driving problems	Learning objectives	Strategies to foster learning	TLS1. Activities and comments Implementation and re-design	TLS2. Activities and comments Implementation and re-design
How does electric current work? Macro and micro aspects in an electrical circuit	O.1, O.4	a.- Familiarizing students with analysis of the phenomena that shows relations between current at microscopic and macroscopic levels: -. Defining electron current -.Defining conventional current -.Presenting quantitative relations between electron current and conventional current	Activities to define and use electron current and conventional current (implement strategies a and b): the first 6 activities of TLS1	Activities to define and use the concept of electron current and conventional current (implement strategy a): 3 first activities, the fourth activity a Worksheet (WS1) to discuss the micro and macroscopic point of view of electric current (implement strategies a and b) of TLS2
How does the mechanism that produces the current and the movement of electrons work?	O.3, O.4	-. Introducing micro- and macroscopic points of view of electric current	Activities to define the gradient of surface charges and the electric field in the wire (strategies b and c): the following 6 activities of TLS1	Activities to define the gradient of surface charges and the electric field in the wire (strategies b and c): the following 5 activities of TLS2
		b.- Organizing empirical information and proposing hypotheses about the relations between E, ΔV and current.	Activities to define the role of the battery in a dc circuit from the microscopic and macroscopic point of view (strategies b and c): the following 3 activities of TLS1	Activities to define the role of the battery in a dc circuit from the microscopic and macroscopic point of view (strategies b and c): the following 4 activities of TLS2
What is the relation between role of the battery and the electric field in the wire?	O.3,O.2, O.4	c.- Proposing hypotheses about the role of electrical field in the wire. Applying the model to initial transient and stationary state current d.- Applying micro (GSC) and macro (Kirchhoff' s law) explicative model to simple dc circuits	Problems to analyze simple resistive dc circuits from macroscopic and microscopic models (strategy d): the following 4 activities of TLS1	Problems to analyze simple resistive dc circuits from macroscopic and microscopic models (strategy d): the last four activities.

descriptively without justifying the statements. For example, for A.15, a student writes in his workbook:

> *"The battery produces a voltage difference between its poles that makes the electrons move from low potential to high potential and a current is produced in the circuit cable. At a microscopic level, there is an electric field that pushes the electrons and produces the electric current."*

Very few students reason at a microscopic level along the lines of "the battery produces a charge gradient on the surface of the wire. This charge gradient produces an electric field in the wire that generates a current of electrons." These results imply that we should not underestimate the multilevel reasoning difficulties that we detected in our previous study [23] and that it is necessary to reinforce the argumentation activities using both models (see Table IV).

<table>
<tr><th>Activities (TLS1)</th><th>Activities (TLS2)</th></tr>
<tr><td>A.3.- In a copper wire, the current of electrons is about i=3.4 x 10^{18} electrons/s. This is a huge number of electrons passing through a section of the wire every second. But, how long does it take for an electron to travel a metre along a copper wire?
Make a prediction: a) 10^6 seconds; b) 1 second; c) 10^{-6} seconds; d) Something else,

A.4. Suppose that 100 mA are drifting through a copper wire. The diameter of the wire is 1 mm (A = 8 10^{-7} m^2) and the density of mobile electrons in copper is 8.4 10^{28} m^{-3}. Calculate: a) the drift speed of the electrons; b) How long does it take for a single electron in the electron sea to drift 1 m along the wire?</td><td>A.3.- In a copper wire, the current of electrons is about i=3.4 x 10^{18} electrons/s. This is a huge number of electrons passing through a section of the wire every second. But, how long does it take for an electron to travel a metre along a copper wire?
Make a prediction: a) 10^6 seconds; b) 1 second; c) 10^{-6} seconds; d) Something else.

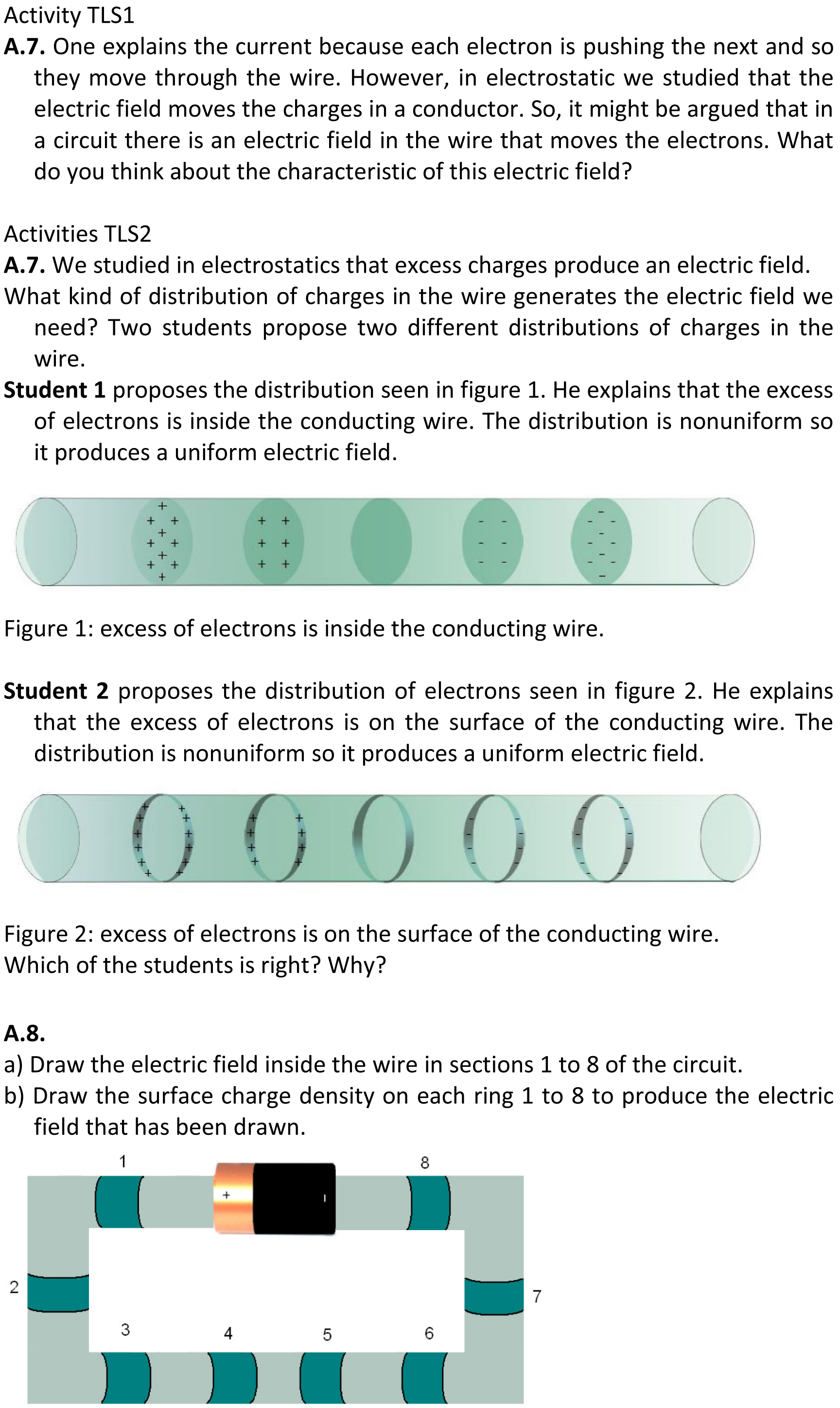
A.4. Suppose that 100 mA are drifting through a copper wire. The diameter of the wire is 1 mm (A = 8 10^{-7} m^2) and the density of mobile electrons in copper is 8.4 $10^{28}$$m^{-3}$. Calculate:
a.- What is the drift speed of electrons?
b.- How long does it take for a single electron in the electron sea to drift 1 m along the wire?
c.- If the speed of the electrons in the wire is 9.41X10^{-6} m/s and electrons need 29.5 hours to move one metre, why does the light in a football stadium come on almost instantly when you flip a switch 300 metres away?
A.5.- WS1. Find the relationship and reason
<table>
<tr><th>Microscopic point of view</th><th>Macroscopic point of view</th></tr>
<tr><td>The velocity of the electrons in the wire in a circuit is: a) Slow; b) Fast; c) Almost light speed</td><td>The effects of the current in a circuit are: a) Slow; b) Fast; c) Almost light speed</td></tr>
<tr><td>The force that acts on electrons is produced by: a) E; b) ΔV; c) Other</td><td>In a circuit with I current, the multimeter measures: a) E; b) ΔV; c) Other</td></tr>
</table></td></tr>
</table>

FIG. 1. Changes made to the learning path from the macro-micro analysis of the electrical current (objective 4).

On the basis of the data obtained from the teacher's diary, students' workbook, the feedback received by the classroom observers and the results of the post-test, we refined the sequence of the contents in TLS1. The changes are mainly made in reformulating activities to adapt them so that the students understand their aim (metacognitive difficulty) and to stimulate production of hypotheses and arguments for the conclusions. The data obtained indicate that the students have no difficulty in understanding the order in which the topic contents are presented, and no changes were made in presenting the learning path. The second version of the TLS applied in the spring semester of the 2016–2017 and 2017–2018 academic years presents the rewritten activities and the added worksheets. Writing up new activities is focused on promoting argumentation about conclusions at the macro- and microlevels from the start of the TLS and in each of the four sections.

The quantitative analysis of the questionnaires included in Sec. III B 2, gave researchers the information needed to reformulate some activities and to introduce worksheets to overcome the detected difficulties. As an example, we can see that after the implementation of TLS1 students' understanding of the macroscopic point of view of the dc circuits is lower for the experimental group in comparison with that of students from the control group (see Q4 Table IV). Based on this result some extra activities were added in a worksheet.

In this study, data from the external observers' reports did not provide information relevant to deciding on changes to the TLS. These reports conclude that the classroom



Activity TLS1

A.7. One explains the current because each electron is pushing the next and so they move through the wire. However, in electrostatic we studied that the electric field moves the charges in a conductor. So, it might be argued that in a circuit there is an electric field in the wire that moves the electrons. What do you think about the characteristic of this electric field?

Activities TLS2

A.7. We studied in electrostatics that excess charges produce an electric field.

What kind of distribution of charges in the wire generates the electric field we need? Two students propose two different distributions of charges in the wire.

Student 1 proposes the distribution seen in figure 1. He explains that the excess of electrons is inside the conducting wire. The distribution is nonuniform so it produces a uniform electric field.

Figure 1: excess of electrons is inside the conducting wire.

Student 2 proposes the distribution of electrons seen in figure 2. He explains that the excess of electrons is on the surface of the conducting wire. The distribution is nonuniform so it produces a uniform electric field.

Figure 2: excess of electrons is on the surface of the conducting wire.

Which of the students is right? Why?

A.8.

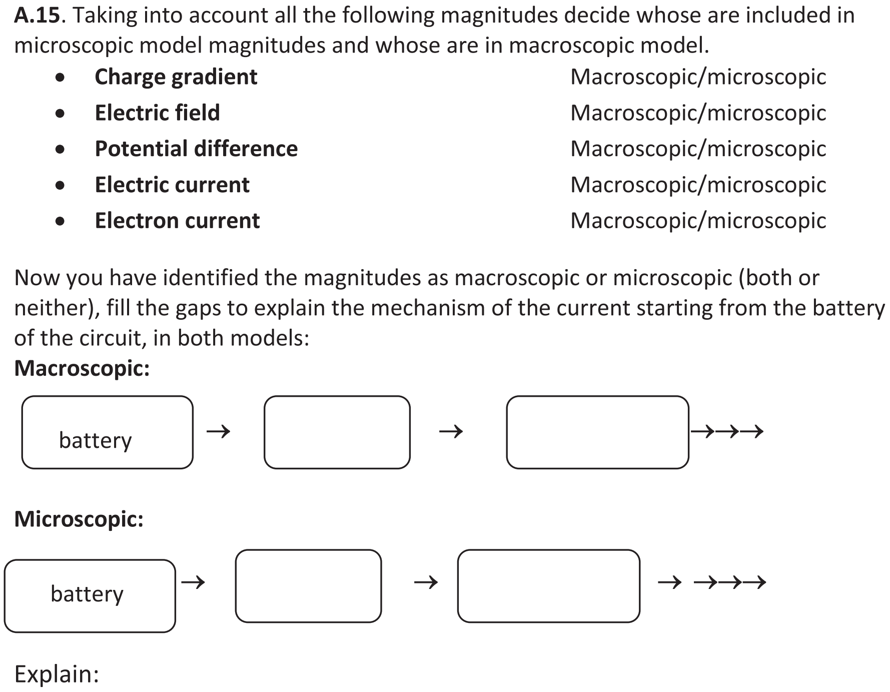
a) Draw the electric field inside the wire in sections 1 to 8 of the circuit.

b) Draw the surface charge density on each ring 1 to 8 to produce the electric field that has been drawn.

FIG. 2. Changes made and new activities in relation to the students' difficulties in relating the electric field and the charges generating it (objective 3).

practices of teachers implementing the TLS generally converged with the teaching strategies and objectives of the programmed activities. This result was to be expected since the teachers who implemented the sequence were also the designers of the TLS. In cases where this will not be the case, one might expect that this instrument will provide more relevant information.

The TLS contains each activity alongside the corresponding comments compiling the teacher's guidelines. These guidelines are meant to help teachers follow the TLS according to the objectives, pointing at the activities that are required to develop the TLS correctly and, at the same time, giving freedom to teachers in relation to the complementary activities.



A.15. Taking into account all the following magnitudes decide whose are included in microscopic model magnitudes and whose are in macroscopic model.

Charge gradient	Macroscopic/microscopic
Electric field	Macroscopic/microscopic
Potential difference	Macroscopic/microscopic
Electric current	Macroscopic/microscopic
Electron current	Macroscopic/microscopic

Now you have identified the magnitudes as macroscopic or microscopic (both or neither), fill the gaps to explain the mechanism of the current starting from the battery of the circuit, in both models:

Macroscopic:

Microscopic:

Explain:

FIG. 3. Activity A.15.

2. Results regarding students' understanding

To see how much students had improved their understanding in relation to the learning objectives of Table I, we used a pre- and post-test design. The post-test was given to students from experimental groups and control group students in exam conditions and the result was included as a part of the final mark for the subject unit. The scores for each group were compared. To decide whether there were any significant differences between the experimental and comparison groups, the two-tailed Fisher exact test was used for the usual level of confidence of 5% or less [85]. There were no significant differences between the experimental and control groups on the pretest, so the results are grouped together in the tables. Pretest and post-test questions were similar. Some of them have been discussed in previous papers on student difficulties concerning macro-micro relations in the dc circuit [23]. The questions of the post-test are shown at the end of the paper (Appendix B). We summarize the relation between post-test questions and objectives in Table III.

Each student's answer to the questions was rigorously analyzed. First, a draft set of descriptive categories was proposed for each of the questions. Subsequently, the answers were reread, and each response was tentatively assigned a category. When there was disagreement about a descriptive category or the relationship of responses to a specific category, this was resolved by using evidence of student understanding as a reference [86].

The answers to the questions were grouped into the following categories:

A. Correct answer and explanation to the question.
B. The answer includes one or more of the difficulties mentioned (D.1 to D.4) and/or a new difficulty.
C. "*Ad hoc*" explanations that are limited to describing the phenomenon without explaining it or that represented rote learning without logical consistency.
D. Incoherent or no answer.

The main purpose of Q1 and Q2 is to see whether students recognize electric field and potential difference as the same concepts in electrostatic and electrodynamics contexts.

TABLE III. Relationship between the aim of question and the learning objective.

Questions	Learning objectives
Q1	O.1. The equivalence of the concept of electric field in electrostatics and electrodynamics
Q2	O.1. The equivalence of the concept of potential difference in electrostatics and electrodynamics
Q4	O.2 Ohm's law at the macroscopic level
Q5	O.3. The influence of the gradient of surface charges on current in the circuit
Q3	O.4. Relationship between current (macroscopic) and electric field (microscopic)
Q6	O.4. Macro-micro relationships when applying 2 Kirchhoff's rules

In situation 1 of question Q1, there is a conducting tube in which both ends are charged. One is positively charged and the other is negatively charged. As shown in the diagram, there is an electric field at point P. On the other hand, situation 2 shows a circuit in which there is also an electric field between points A and B. The electric field of the situation 1 is created because of a separation of charges between the ends. In the other case, the battery (electromotive force) is capable of maintaining a potential difference so that the circuit is in steady state, but in both cases the electric field is generated by electric charges, so it has the same source. Hence, there is an electric field through the wire that makes the electrons move until the battery runs out. In question Q2 students have to apply the same concept of electric potential to explain their reasoning, so it is clear that student 1 is correct.

Question Q3 gives an electrodynamics context and investigates students' difficulties in understanding the concepts of current (Q3.1 macroscopic level) and electric field (Q3.2 microscopic level) in a circuit. To do this, we use an electric circuit made up of a battery and a copper wire with different diameters. We analyze whether the students are capable of explaining the relationship between current and electric field. We expect that students should know that in a steady state, current must be constant at every point of a wire so the electric field must be bigger when the material is a worse conductor and/or the diameter of the wire is smaller.

Question Q4 assesses whether the students understand simple electric dc circuits at a macroscopic level. We examine whether the students know how to apply Ohm's law in simple circuits with resistors. The application of the macroscopic model of a simple dc circuit must guide the students to compute that when the circuit is open the current is 3A and when is closed 4.5A. Question Q5 investigates students' knowledge relating to the cause of the electric field within the wire that moves the charges and produces the electric current (surface charge gradient model). To do this, students should know how to identify which charges produce the electric field and how they are distributed. The option that generates a constant electric field needed to understand a microscopic model of a circuit is option 3. Students should argue that a constant electric field is generated when the gradient of charges is constant in the wire despite the amount or sign of the charge. Question Q6 aims to determine whether the students are capable of relating the circuit's energy equilibrium equations in different situations. To do so, we set two strategies for calculating the energy equilibrium, one at a microscopic level and the other at macroscopic level. The energy balance of a circuit could be described from the macroscopic point of view (student 1) and the microscopic point of view (student 2). In Q6, both students provide a correct energy balance; student 1 is analyzing the energy balance of the whole circuit (including the nonideal battery) while student 2 is analyzing the energy between the poles of the circuit (not including the battery).

Table IV shows the frequency of correct answers for the questions. During the three years that the experience lasted, the percentages of correct answers in the pretest did not vary significantly, so we have presented the average of the percentages in the first column.

The results from Table IV show that, for the first version of the TLS in 2015, results for the experimental and control groups differed significantly ($p < 0.001$) for all questions except Q1, Q3, and Q4. Performance in the experimental groups is relatively low for questions Q3 and Q6, which are

TABLE IV. Percentages of the correct answer for all questions and the significance level (computed using the two tailed Fisher exact test) of comparisons between the control and experimental groups. Experimental groups in Spr. 15 (E-TLS1), Spr. 16 (E-TLS2), and Spr. 17 (E2-TLS2). Comparison groups in Spr. 15 (C-15), Spr. 16(C-16), and Spr. 17 (C-17).

		Post-2015–16			Post-2016–2017			Post-2017–2018		
	All courses	C-15		E1-TLS1	C-16		E2-TLS2	C-17		E3-TLS2
	Pre ($N = 238$	$N = 115$		$N = 75$	$N = 98$		$N = 60$	$N = 103$		$N = 65$
Questions			p			p			p	
Q1	0.0	29.5	0.52	35.0	42.0	<0.001	85.5	32.5	<0.001	84.0
Q2	15.0	18.0	<0.001	70.0	16.5	<0.001	75.0	17.5	<0.001	80.0
Q3	0.0	3.5	0.07	10.5	5.0	<0.001	35.5	5.5	<0.001	48.0
Q4	30, 0	70.0	0.007	61.0	71.0	0.71	74.5	72.0	1	73.0
Q5	0.0	8.5	<0.001	47.5	14.5	<0.001	77.5	7.0	<0.001	78.0
Q6	0.0	3.5	0.003	15.5	8.5	<0.001	43.5	5.0	<0.001	49.0

related to the macro-micro relationships that constitute the core learning of the TLS. Furthermore, the significance in Q4 is in favor of the control groups. The results for the TLS2 in 2016 and 2017 show a significant improvement in the performance of the experimental group. In addition, results for the experimental and control groups differed significantly ($p < 0.001$) for all questions except Q4. The result of question Q4 was expected because it tests students' learning of Ohm's law, the macroscopic aspect of the circuit model. In TLS1 the focus on the microscopic model resulted in weak performance by the experimental group. After the redesign, there is not a difference between control and experimental groups.

Regarding students' learning, we examine also how the frequency with which students experience difficulties has changed in relation to defined objectives. It should be noted that difficulties identified in the literature that are *not* featured in Table IV appeared with very low frequency (less than 3%). Therefore, we are going to refer to four difficulties that were located in category B for each question in the analysis. The difficulty D1 (difficulties in applying E and ΔV in both electrostatic and electrodynamic contexts) was found in responses to questions Q1 and Q2. It is evidenced in answers that explicitly show the definition of the quantity only in the macroscopic context. The following are typical answers showing this difficulty:

> *"In the cylinder there is an electric field because there are charges on the bases of the cylinder" (question Q1, student 34 CG)*
> *"The electric field is generated by the separation of charges in the cylinder and in the circuit, by the battery" (question Q1, student 72, EG)*
> *"I agree with student E2, the first equation is to calculate the electric potential in electrostatics. Ohm's law is used in circuits" (question Q2, student 45 CG).*

In the same way, in question Q4, the explanations that incorrectly apply Ohm's law have been included in category B. This category includes answers that explicitly show difficulty D2 (difficulties in analyzing the topology of the circuit at the macroscopic level).

The same criteria were followed for difficulty D3. (Difficulties in analyzing the current at the microscopic level). The analysis only takes into account answers that explicitly indicate that the charges are contained in the battery and that the quantity of charges decreases in the wire as the distance to the battery increases (question Q5, category B) or the answers which are limited to performing a macroscopic analysis (question Q3, category B). This does not mean that the other answers are correct, but only those responses that explicitly reflect difficulty D3 have been assessed to category B. The same criterion has been followed with difficulty D4 in question Q6. The following are some examples of this type of difficulty:

> *"The current is greater when the diameter is smaller since when the cable is narrower the charges go faster" (question Q3, student 75 CG).*
> *"Electron density is higher near the negative pole. The negative charges are in this pole. I choose Fig. 2" (question Q5, student 39, CG).*
> *"The charges are in the battery and go to the circuit, so I think that there are more density of charges near to the poles, like in Fig. 2" (question Q5, student 92, CG).*

Fluctuations in the percentages are not considered in absolute values, nor are statistical differences sought, but an attempt is made to observe any changes in the frequency with which students experience difficulties, as shown in Fig. 4.

Around 60% of the control students demonstrate difficulties in explaining that the electric field and electric potential have the same meaning in electrostatic and electric circuits (difficulty D1). This difficulty persists among students in the experimental group, but much less frequently (34% TLS1, about 10% TLS2). The frequency of difficulty D2 is similar in the two groups and both groups are performing similarly with respect to providing correct answers. This result was to be expected since the teaching of this part of the program is very similar for both experimental and control groups. In difficulty D3, related to the understanding of the Surface Charge Gradient model (questions Q3 and Q5), between 30% and 40% of the control students explain that the charges are in the battery and its density within the wire decreases with distance to it. In the case of the experimental group, for TLS1 the percentage of difficulty remains the same as in the control group (around 30%). However, in the redesigned TLS2 this difficulty is rarer (around 10%).

Regarding the difficulties in analyzing the circuit both at macroscopic and microscopic levels (difficulty D4). The data seem to indicate that there is no improvement in overcoming this difficulty between the control and experimental groups. However, the number of incoherent or missing responses is much higher in the control groups than in the experimental ones. We think that there is a progression in the learning of the experimental students, where the learner abandons "naive ideas" but their understanding is incompletely addressed [87]. The TLS1 and the TLS2 help the students to understand the microscopic surface charge gradient model, improving significantly the number of correct answers (see Table IV, question Q6). However, there was also an increase in those answers that pose an incomplete microscopic model that does not consider the relationship between the electric field and the potential difference.

C. Discussion of generalizability

Our study shows that the experimental group students achieve a stronger conceptual understanding of electric

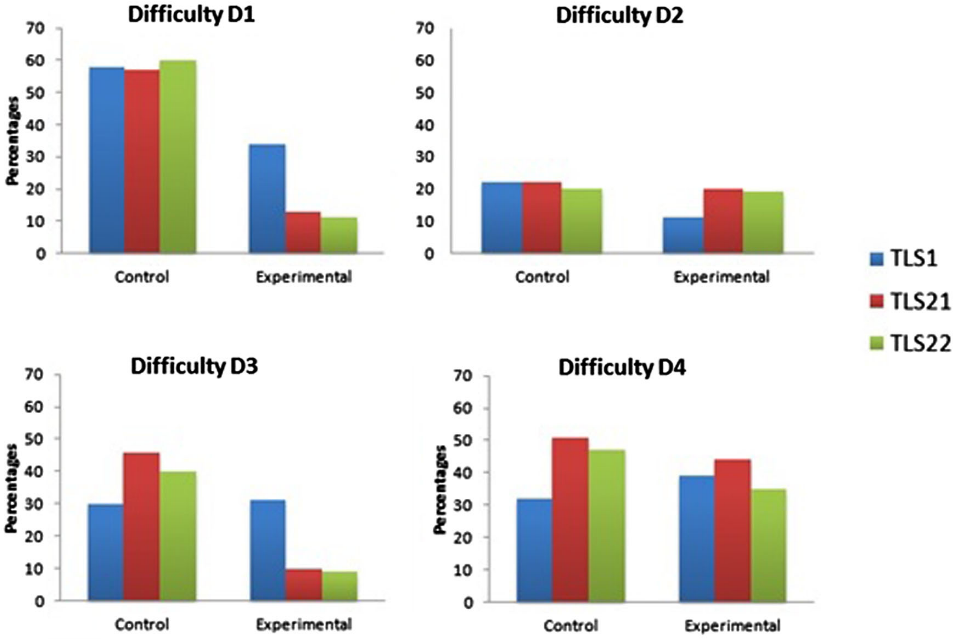


FIG. 4. Evolution of learning difficulties in control and experimental groups.

circuits. Because the example is limited to a sample from one university (UPV-EHU; University of the Basque Country), we cannot generalize about benefits of our TLS in terms of learning in general, even though some of the teaching and learning difficulties encountered are similar to those detected in other international studies. In our future studies, we plan to share this way of TLS design and evaluation with other universities. However, we argue that theory development is not always based just on results for large samples, but also on propensities and processes. Rather than generalizing from a random sample to a population (statistical generalization), many research approaches aim for a generalization to a theory or model by presenting findings as particular cases of a more general model [88]. In this approach, explanations of what happens in the classroom are oriented to the process based on what happens in response to particular interventions. Adopting a view of process-oriented understanding of causality as plausible, on the basis of circumstantial evidence of observed processes that what happened is most likely caused by the intervention [89].

IV. CONCLUSIONS

The purpose of this study was to apply the DBR methodology to make explicit the choices in material design and in the systematic refinement of the TLS based on assessment tools. The assessment of the teaching material that allows its successive refinement is frequently not considered when proposing a new approach. Our application to the topic of "fundamentals of dc circuits" indicated that the DBR methodology has had an impact not only on the final learning results, but also on aspects relating to the type of work performed by students.

We agree with Cobb *et al.* [60] that "beyond just creating designs that are effective and that can sometimes be affected by 'tinkering to perfection,' a design theory explains why designs work and suggests how they may be adapted to new circumstances." (p. 9). In our research we have decided to apply the DBR methodology because it allows us to build and refine a teaching strategy for our chosen topic—fundamentals of dc circuits—with a higher probability of obtaining a viable instructional approach, but also because it helps to build design principles and didactical tools to design TLSs. DBR methodology emphasizes the importance of justifying the decisions made in the design and how and why to use the activities and the evaluation tools. This is evident in the way that we use it for designing the learning objectives explicitly based on epistemological and psychological arguments, rather than on research group idiosyncrasy. Later in the evaluation, following DBR, we introduce some tools that involve the evaluation of the design itself and the learning obtained by students. This evaluation includes the students' progression when overcoming learning difficulties.

A novel aspect of this research is the didactical tools used in the design. We have shown the usefulness of the epistemological analysis as a didactical tool to ground and, when appropriate, change the curriculum aims according to the education level. Likewise, "learning demands" have been used as a tool to guide the design of learning activities so that they will be located in the Vygotskian zone of potential development of the students. We have used driving problems that are related to one or several learning aims, and include a set of activities. Carrying out these activities involves conceptual contents and scientific practices. Solving them fosters achieving the learning aims associated to the driven problem. These didactical tools can be seen as "humble theories" for the design of TLSs.

Another novel aspect, in relation to the chosen design principles, is the evidence we have brought forward that a well-founded design of the materials is not enough; rather it requires confronting it with its classroom implementation and analyzing the coherence between the TLS activities aims and the obtained students' results. To that end we have presented data obtained with the evaluation tools on the quality of the TLS.

This study provides an example of applying the DBR methodology in a specific topic of physics at first level of university or college. The example shows the improvement in the experimental group students' comprehension compared to that of the control students. The results in terms of the learning achieved are hopeful and demonstrate a significant statistical improvement. The assessment analysis is not limited to quantifying correct or incorrect answers in the pre and post questionnaires. Answers are categorized and analyzed to represent an evolution in comprehension difficulties. Qualitative analysis of the answers in categories has led us to consider student comprehension difficulties that are demonstrated in some cases, which are persistent in the learning in the new TLS, and in others, which are demonstrations of an evolution in the understanding towards states that are more in line with scientific interpretation.

Developing teaching learning sequences continues to be a common goal in the community of science education. The application of DBR and the example shown here may provide guidance for curriculum designers and teachers beyond description of merely "good ideas" or applications without evaluation.

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APPENDIX A: DESIGN TOOLS

We have used design tools, as defined in the literature [42], in the design process of the TLSs. We have considered two design tools: epistemological analysis, and learning demand.

The *epistemological analysis* design tool considers the internal structure of the target scientific domain to inform a proposal for the construction of that knowledge in a specific educational environment. The result is a set of conceptual components that should be articulated by the students.

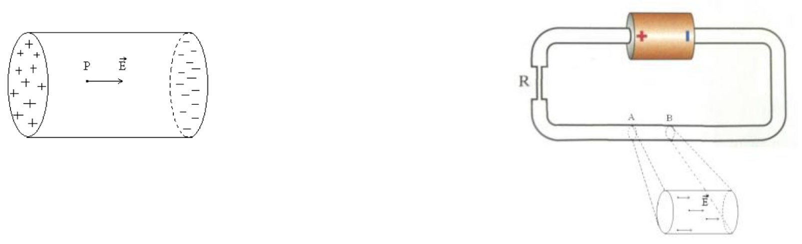
Next, we analyze the literature, if there is one, on the difficulties that students encounter with the topic and possible solutions proposed to overcome these difficulties. If the PER literature does not provide information on students' ideas regarding the topic's specific concepts, we conduct an original, empirical investigation thereof. The epistemological analysis and findings about students' difficulties guide the formulation of provisional learning objectives, which in turn shape the learning path of the TLS.

The epistemological and ontological differences that might exist in the evolution of scientific theories or the shift from one theory to another one, have particular importance in the determination of students' learning difficulties [90]. For instance, the quantum concept of the atom does not have the same ontological category as that of the classical concept of the atom. Knowledge of the epistemological and ontological barriers in the topic of dc circuits have helped us defining the "driving problems," the resolution of which includes a set of activities and guides the sequencing of the TLS activities [91]. A teaching strategy that guides students facing these driving problems can provide them an initial idea of the intended learning aim to be achieved through the associated activities [92,93].

The *learning demand* design tool [24] is used to analyze the ontological and epistemic differences between the students' ideas and the defined learning objectives. It makes a qualitative evaluation of the differences between the students' ontological and epistemological understanding of the concepts to be taught and the intended scientific understanding at the end of the teaching. These differences will guide the TLS learning path by highlighting both the *type* and *degree* of difficulty that we can expect the students to encounter. At this point, if necessary, learning objectives are reformulated. It is crucial to clearly and explicitly define these learning objectives if we want the results of the TLS assessment to be useful in future designs.

APPENDIX B: QUESTIONNAIRE

Q1.- What is the cause of the electric field in situation A and situation B? (see figure 5)


Situation A:

Situation B:

FIG. 5. Representation of situation *A* and *B*.

Q2.- A student E1 states that the potential difference between points A and B can be calculated, in both situations, using the equation $\Delta V = \int_A^B \vec{E}\, dl$. Another student E2 does not agree and states that the equation $\Delta V = \int_A^B \vec{E}\, dl$ is only valid to calculate the electrostatic potential difference (situation 2) and that the potential difference in situation 1 is calculated using Ohm's Law: $\Delta V = I\, R$. See figure 6

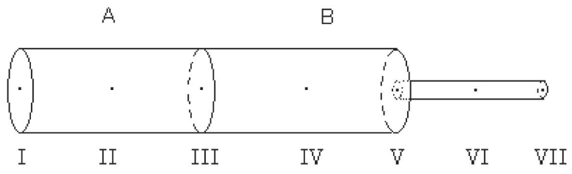
Which student do you agree with? Explain your answer.


Situation 1:

Situation 2:

FIG. 6. Representation of situation 1 and 2.

Q3.- As it is shown in figure 7, a conducting cylinder is made of three segments of equal length: material A with diameter D, then material B with diameter D and ultimately material B with diameter D/2. The two ends, the two boundaries, and the three segment midpoints are all labelled. Material A is a better conductor than material B.



Once the cylinder is connected to a battery and current is flowing, sort these amounts from highest to lowest:

Q3.1: Current at II, IV and VI.

Q3.2: Electric field at II, IV and VI.

Explain your answers

FIG. 7. Conducting cylinder with different segments.

Q4.- calculate the current of the circuit.

a) Before closing the switch.
b) After closing the switch.

Explain your answers

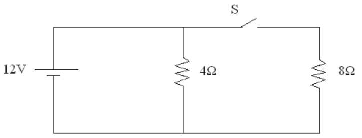


FIG. 8. Resistive circuit.

Q5.- Which of the next schemes (see figure 9) shows the correct distribution of the excess charge on the surface of a circuit?

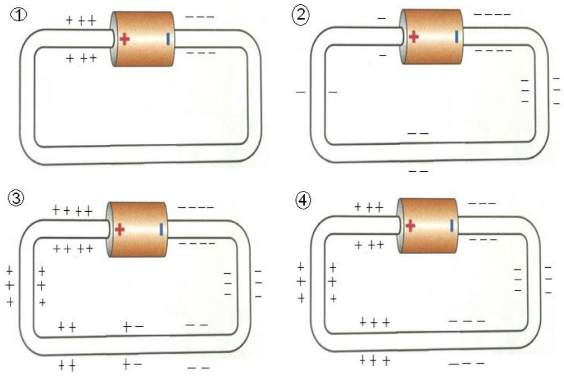


FIG. 9. Four schemes for distribution of the excess charge on the surface of a circuit.

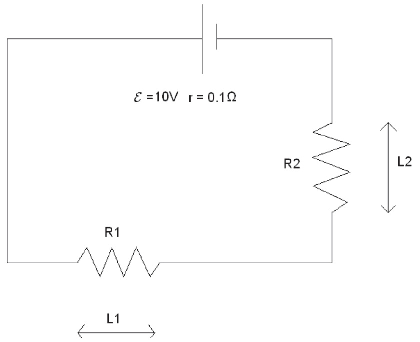
Q6.- Two identical resistors are connected to a real battery as shown in the figure 10.

The student E1 carries out the circuit energy balance according to the equation:

$$\epsilon - I \cdot r - I \cdot R_1 - I \cdot R_2 = 0$$

Student E2 carries out the circuit energy balance according to the equation:

$$\Delta V = E_1 \cdot L_1 + E_2 \cdot L_2$$



Which student do you agree with? Explain your answer

a) Student E1.
b) Student E2.
c) Both.
d) No one

Note: E_1 and E_2 mean the electric field in the resistances R_1 and R_2. L_1 and L_2 are the lengh of the resistances

FIG. 10. Electrical circuit.

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