Chapter 13
Designing Teaching Learning Sequences Based on Design-Based Research

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Abstract In this chapter, we put forward a proposal for the design of teaching and learning sequences in high school and university. We will connect our proposal with relevant contributions on the design of teaching sequences, ground it on the design-based research methodology, and discuss how teaching and learning sequences designed according to our proposal supposes an research on physics education. An iterative methodology for designing the teaching and learning sequence (TLS) is presented in the teaching of fundamentals of dc circuits.

13.1 Introduction

Since the 1980s of the last century, research in physics education has repeatedly shown that students do not achieve the expected learning. Secondary and university students, despite years of schooling, still have alternative conceptions to scientists (Duit 2009). From these works, research in physics education has developed design-based research approaches. The Design-Based Research is based on the fact that we can learn important knowledge about the nature and conditions of teaching and learning by trying to design and develop educational innovation in classroom settings. Design-Based Research (hereinafter DBR) necessarily includes the design, implementation, and evaluation of Teaching/Learning Sequences (TLS) as interventional research that generates new pedagogical knowledge (Kortland and Klaassen 2010).

TLS can be broadly defined as "an interventionist research activity and product, similar to a traditional curriculum unit, that includes well-researched teaching-learning activities empirically adapted to student reasoning" (Méheut and Psillos 2004). Therefore, TLS design reflects the interrelationship between the development of tools and learning environments and the development of theory. This

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B. G. Sidharth et al. (eds.), *Fundamental Physics and Physics Education Research*,
https://doi.org/10.1007/978-3-030-52923-9_13

interconnection is a complex and cyclical process in which the principles of general education are applied to the teaching of specific subjects in specific contexts (Lijnse 2004). At each stage of development there are opportunities to test conjectures about student learning and to refine those conjectures based on experience, as well as to redesign the SEA proposal. As a consequence, researchers have defined development frameworks, to be used by designers, as interfaces between major theories and the needs associated with developing the SEA on specific topics. The improvement obtained in research based on the use of TLSs has been shown in some cases to be significant, even for teachers with little experience in using TLSs (Ametller et al. 2007; Savall-Alemany et al. 2019; Savinainen et al. 2017).

A broad coherence between theoretical or methodological efforts in experimental design approaches could be expected, but as we have seen in the literature this is not the case. Partly due to the great breadth of research covering a wide variety of school interventions with different specific aspects (cognition, cognitive development, teaching strategies, classroom interactions). DBR approaches have involved improving existing material by designing research-based teaching activities. Therefore, the teaching materials are designed based on the results of the research and can be evaluated accordingly. Most of these approaches share some common characteristics. They are generally informed by empirical evidence of students' previous conceptions, an epistemological analysis of objectives, theoretical perspectives on learning that are aligned with the cognitive constructivist approach and the specific educational context. Articles, such as those cited above, generally present evidence of student learning. However, less frequently it is discussed how the above considerations informed the design, implementation, and evaluation of TLS. Therefore, 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 made regarding design and implementation; (b) a detailed specification of teaching strategies, which are often implicitly addressed under the label of "active teaching" or "active learning"; (c) a comprehensive assessment procedure (that is, one that goes beyond the learning achieved); and (d) a detailed description of the iterative refinement process. The lack of such explicit descriptions makes it difficult for the science education community to interpret the results presented, propose a systematic design improvement, and build on the findings.

Although research based on DBR design has the potential to offer a useful set of methodological tools to deal with the above mentioned problems, there are issues that must be addressed in order for this methodology to be credible for the community. Questions such as: what are the key elements that define design-based research and what differentiates it from other types of research, or what evidence is offered to support the achievements of this type of research should be addressed. In this chapter, we intend to present the key elements of the DBR methodology that have been agreed by the community and that characterize this methodology. Second, we will present an example of the application of the DBR methodology focusing on the topic of "Fundamentals circuits" for introductory physics courses in the area of Mechanics. In this contribution we will show the part of the design of the TLS. In particular, examples will be given on three aspects: (a) to justify the contents of TLS;

(b) To evaluate students 'difficulties; (c) To define the learning demands. We will finish with a discussion on the advantages of the DBR methodology in order to make the TLS design criteria explicit. Making these criteria explicit helps teachers to understand the advantages and usefulness of the TLS and, furthermore, contributes to developing their pedagogical content knowledge.

13.2 DBR Phases and the TLS Design

DBR is a cyclical process that typically comprises three phases: design, teaching experiments (implementation), and retrospective analysis (assessment) (Anderson and Shattuck 2012; Easterday et al. 2014; Barab and Squire 2004).

The design phase leads to an initial product (the 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 and the epistemological analysis of the topic. In the design phase, the clear and explicit definition of the learning objectives is key if we want to evaluate the achievements obtained. 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. Next, we use the "learning demand design tool" (Ametller et al. 2007) to analyze the ontological and epistemic differences between the students' ideas and the defined learning objectives. These gaps will guide the TLS learning path by highlighting both the type and degree of difficulty that we can expect the students to encounter.

In summary, the phase of design includes learning goals, information on students' relevant difficulties, structured activities to implement in classroom and guidance on how the teacher can support the teaching processes (see Table 13.1).

Once the objectives and sequence of the program have been established and justified, a first version of the activities that made up the sequence to be implemented is designed. The documents that are needed for the implementation of the SEA are generated, usually include work materials, based on epistemological analysis and learning demands, assessment guidelines related to defined learning objectives, and material for teachers with information on the use of work materials. Not all aspects of these materials are directly derived from the different elements of the design and, therefore, it is important to inform the teachers who are going to use the TLS, which

Table 13.1 Design phase

Analysis of the instructional context and of the epistemological aspects of the topic	Analysis of students' prior ideas, and conceptual and reasoning difficulties	Need for interactive environments that reflect the skills and attitudes of scientific research
Learning objectives	*Learning difficulties* and *Learning demands*	*Teaching strategies*
Building specific tasks that lead to a proposed learning trajectory *TLS activities* *Teacher's guide for implementing the TLS*		

aspects are referents of theory and research, and which are contributions personal designers based on their Pedagogical Knowledge of Content.

In the DBR methodology, implementation is the part where TLS is applied in the classroom. The evaluation stage of the DBR methodology involves an iterative process that carries out tests throughout the design and redesign process. In our proposal, the design of the TLSs is empirically validated, through two dimensions (Nieveen 2009). In the first dimension, the quality of the sequence is analyzed, that is, the ability of the teaching material to involve students in the task. In particular, implementation difficulties are analyzed in relation to the students' understanding due to drafting problems of the activities. Implementation time problems and difficulties in designing new content activities are evaluated. In the second dimension, the learning achieved by the students in relation to the defined objectives is evaluated. This evaluation includes understanding concepts, laws and theoretical models and, using the procedure of scientific activity to solve problems.

In this chapter, we will show two examples. First example of the design of the DBR, that is, about the first phase of the DBR (design TLS) in the topic of DC circuits for introductory physics courses. Second example is about testing the quality of design by the redesigning of the activity.

13.3 Theoretical Informed Learning Goals of the Sequence

This section provides a general description of the design process, which shows how the epistemological and cognitive analysis underpins the election of the design learning aims. On the first place, we will show how general educational theories underpin the design tools, which we use to carry out the "fine grain" analysis of the specific contents which will be taught in the TLS during the first phased of the DBR. The first step is focused in teaching context. In our case the context is the topic of the "Fundamentals of DC circuits" addressed to Physics introductory courses at University. The aims of the syllabus are defined according to the educational level of application.

Firstly, the contents of the curriculum set out in the standards for the chosen level of education are taken into account. Secondly, we consider the need to justify the sequence of contents of the program. In these first two steps, the epistemological analysis of the content will help to justify the contents and laws included, as well as their sequence. The epistemological analysis includes the historical development of the topic, the difficulties that the scientific community had to overcome and the arguments that were used to build new explanatory concepts and models. Epistemological analysis allows us to select the key aspects of the topic that contribute to defining learning objectives. The epistemological analysis of the content is used as a didactic tool to avoid definitions of the program based on the idiosyncrasies of the designers or traditional curricular choices. Furthermore, the defined objectives can be used to sequence the main problems that must be solved to learn the contents of the program.

Next, we proceed to explicitly justify the chosen content and its sequence. As we have indicated previously, many of the design-based research proposals do not explicitly justify the decisions made regarding the content program and its sequence. The design of a TLS based on the DBR methodology must show the most outstanding elements of epistemological analysis—paradigm shifts, justification of new theories, events of the emergence of new interpretive models—in order to show the relationships between the theoretical framework of the discipline and the objectives chosen to teach the subject. In the example we are considering different discussions in the Physics Education literature about teaching the concepts involved in the explicative model of how DC circuits work (Closset 1983; Liegeois and Mullet 2002; Smith and van Kampen 2011).

The mentioned studies show empirical evidences on the difficulties that students have in learning a scientific model of fundamental of DC circuits with resistors. A summary of the literature is indicated below:

– The fact that most of the students who participated in the aforementioned studies avoid using the concepts of potential to analyze the current in a circuit, indicates confusion in the meaning of this concept.
– A significant percentage of students indicate as a cause of the current the difference in the amount of charge or sign of charges, between the ends of the battery.
– Students often use reasoning based on the "formula" in their description of how a circuit works.
– Many students consider Ohm's law as the general law of the circuit that explains its current and energy balance.
– Most of the students do not relate the macroscopic phenomena (current, potential measurements, resistances ...) and the microscopic phenomena (movement of electrons, action of the electric field on the electrons ...).

The beginnings of electrical theory in the eighteenth and nineteenth centuries are linked to electrostatic phenomena. In this way, one of the first theories on the flow of current in a closed circuit refers to the "electrical conflict" based on the model of the two fluids that leave the battery and are neutralized along the wire. During the eighteenth century, studies were carried out in transient current discharges, in accordance with the development of experimental (Leyden jar) (Bensheguir and Closset 1996). After Volta's discovery, the experimental base expands and new explanatory theories of electric current appear. The concepts of "degree of electrical tension" of a charged conductor and "electromotive force" were introduced by Volta to explain the voltage in electrical conductors that caused the movement of current. During the 1920s, Ohm investigated the conductivity of materials and their resistance to current flow. In this context, Ohm explained the different roles of the current and the potential at a time when they were both quite confused. Ohm used the analogy of the temperature gradient that drives heat transfer to explain the flow of electricity in a circuit through lead wires (Schagrin 1963; Taton 1988). Kirchhoff synthesized Ohm's work and went further by proposing a theory for current flow in electrical circuits. This theory was based on the development of the concept of potential and the analysis of the complete circuit. According to the theory in electrostatics, there could be no volume charge gradient inside the conductor, and Kirchhoff solved the problem by putting a charge gradient on the surface (Whittaker 1987). Furthermore, Kirchhoff experimentally demonstrated that Volta's "electrical voltage" and Poisson's potential function were numerically identical in a conductor and therefore could be reduced to a single concept. Since advances in Kirchhoff's electrical theory, electrostatics and electrokinetics have converged into a single electrical theory (Heilbron 1979). Taking Coulomb's law into account, the theory explained that direct current is due to the flow of electrons under the influence of electrical forces and under the influence of a potential difference across the poles of a battery. Later, with works on the field model of Faraday and, Maxwell (1865), the electrical theory of current circuits received a new impulse. In this interpretation, the electrical currents in cables, resistors, etc., are driven by electric fields. The electric field has its source only in the surface charge distributions on the cable (Jefimenko 1966; Härtel 1993).

The epistemological analysis identifies three key problems: (a) relations between electrostatics and current; (b) relations between macroscopic phenomena and microscopic level models; (c) relations between operative definitions of charge, potential, and electric capacity and their meaning in electrostatics and current.

We consider explanations at macroscopic level those that are focused on the physical quantities, such as resistance, current, and potential difference from the overall perspective of the circuit. Quantities such as conventional current and those defined at the level of operational definitions (for example, Ohms' law or the formula that relates potential and field). Instead, we consider explanations at the microscopic level those that are focused at the local level in terms of electrons, electron current, or charge density (Griffith 2014). After covering electrostatics, students are often confronted with a new situation (e.g., electrokinetic phenomena) that not only leads to new phenomena (charges of movement in a wire) but also challenges their view that an electric field is required for a current to flow in a wire. However, literature show that students do not use to seeing circuits as being driven by an electric field that acts on electrons at the microscopic level (whether or not this results in a conventional current at the macroscopic level) (Hirvonen 2007).

Taking into account the epistemological key problems and students learning difficulties, we defined the learning objectives for the TLS on "Fundamental of DC circuits". Reasoning in qualitative and quantitative terms about the phenomena that occur in electrical circuits involves to develop robust models of the microscopic processes underlying them, which lead to the observed phenomena and their macroscopic explanations (Leniz et al. 2017). Consequently, first of all, it is a question of learning a microscopic model of electrical current in a simple DC circuit with the following characteristics:

LO.1: Recognize that the magnitudes of electric field and electric potential defined in electrostatics are the same as those used in electrodynamics. Knowing how to apply these magnitudes in both contexts.

LO.2: Relate the microscopic electron current model, which is related to the electric field magnitude in the conductor ($i = n\ A\ v_d = n\ A\ u\ E = n\ A\ u\ \Delta V/L$), with the conventional current ($I = \Delta Q/\Delta t$). Knowing how to use the magnitudes of each model in the appropriate context and field of validity ($i = n\ A\ u\ E$; $I = \Delta Q/\Delta t = n\ q\ A\ v_d = n\ q\ A\ u\ E$).

Secondly, here is often a need to find an alternative to a purely macroscopic description. We are often left at the macroscopic scale, with explanations such as "this law, or this other law, tells us that things have to be this way." These types of explanations are insufficient to satisfy students, especially when alternative conceptions appear on the way of learning. So, it will be necessary to define the causal mechanism that generates the electric field inside the wire:

LO.3: Knowing and applying the model of Gradient of Surface Charges (GSC) in relation to the role played by the battery in the production of the distribution of surface charges in the wire. This distribution of surface charges (GCS) produces an electric field inside the wire and consequently, produces a potential difference in the different parts of the circuit.

Thirdly, it is necessary to know how to relate the electrical current microscopic model with the measurements of the ammeters and voltmeters in the different parts of the circuit, for an understanding of the context in which the different laws in a DC circuit are applied. In consequence:

LO.4: Know how to explain the conservation of charge and energy (Kirchhoff's laws) in a simple DC circuit, both at the microscopic level (the electric field that drives the electron sea) and macroscopic (the potential difference between the parts of the circuit). This implies knowing how to relate the conventional current, the electric field inside the wire and the potential difference in different parts of the circuit ($\Delta V = E\ L$; $I = \Delta V/R$; $i = n\ A\ u\ \Delta V/L$; $\varepsilon = \Delta V + rI$).

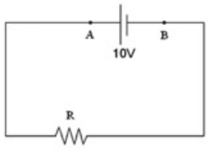
Once the learning indicators have been defined, it is necessary to identify the learning demands. That is, it is necessary to know the magnitude of the gap between the defined learning objectives and the learning difficulties that students usually have in those objectives. This allows the teachers to get an idea of how big or small the cognitive demand is. This will lead to justify the greater or lesser number of activities to work the learning indicator and the process of construction of the concept, procedure or theory. At the beginning of this section, a summary of previous studies showing the learning difficulties on the subject has been made. However, some of the defined indicators have not been specifically investigated and, therefore, it was necessary to carry out a study of learning difficulties.

In a previous study (Goikoetxea 2017), we designed a questionnaire with an emphasis on explanations. We gave 120 students at the University of the Basque Country (Spain) a questionnaire after they had studied the topic in class. We describe here, as an example, one of the questions completed by the students and summarize the results. In the second question Q2 (see Fig. 13.1), the difficulty of students' understanding on the concept of potential difference in electrostatic to electrokinetic

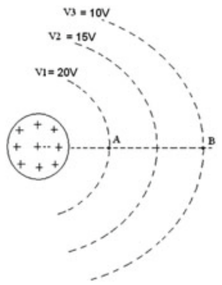
Q2. Student S1 states that the potential difference between points A and B is calculated in the same way by the equation $\Delta V = \int_A^B \vec{E}\, dl$ in the two situations.

Student E2 disagrees and states that the equation $\Delta V = \int_A^B \vec{E}\, dl$, only is used to calculate the potential difference in electrostatics (situation 2), but for the situation 1 the potential difference is calculated by the Ohm's law: ΔV = I R.

Situation 1



Situation 2



With what student do you agree? Explain your answer

Fig. 13.1 Question Q2 related to the content of learning indicator i1. *Q2*. Student S1 states that the potential difference between points *A* and *B* is calculated in the same way by the equation $\Delta V = \int_A^B \vec{E}\, dl$ in the two situations. Student *E*2 disagrees and states that the equation $\Delta V = \int_A^B \vec{E}\, dl$, only is used to calculate the potential difference in electrostatics (situation 2), but for the situation 1 the potential difference is calculated by the Ohm's law: $\Delta V = I\, R$

Table 13.2 Percentages of categories of answers in question Q2

Categories of answers		Percentage (%)
A	The magnitude is the same in both contexts	16.5
B	Two different definitions of the magnitude according to context	75.0
D	Does not answer the question	8.5

is investigated. The question Q2 required students to recognize that the magnitude of potential difference is the same in both electrostatic and electrokinetic and so, the definition of the magnitude is the same (LO.1).

The results of the students' answers to the Q2 question are given as percentages in Table 13.2. The detailed description categories are provided below.

In category A, a minority of students' answers (16.5%) recognize the relations between the equations and students argument about the definition of potential difference. An example:

I agree with the student E1. The general definition of potential difference is expressed by the equation, $\Delta V = \int_A^B \vec{E}\, dl$, and we know that $V = E{\cdot}d$. So, we calculate the ΔV using one way or another depending on each situation.

In the category B, a distinction is made between the definition of the difference of potential in the context of electrostatic and electrical circuits. Three quarter of the students' answers do explain the calculation of the potential difference in each context but with no relation between the two equations. It seems that they consider two different definitions of the same magnitude. A standard example:

I agree with the student E2 because the nature of the field is not the same. In an ohmic circuit we use macroscopic laws ($\Delta V = I\,R$) while in electrostatic they are microscopic".

The results of this question show that students have difficulty in recognizing that the magnitude difference of potential has the same meaning, although different ways of calculating, in the context of electrostatic and electrokinetic. It should be borne in mind that learning objective LO.1 requires a high level of comprehension effort for students and that therefore the demand for learning in this indicator is high. Of course, only one example is shown here, in other works the size of the learning demands for each defined indicator will be shown with a greater number of data.

In the next section we will present an example of the evaluation of the implementation of the TLS, according to the phase test of DBR.

13.4 Testing the Quality of the TLS

As a product-oriented project, one of the essential characteristics of the TLS design and evaluation projects is the re-elaboration of the teaching sequence based on empirical data obtained during its implementation in an educational intervention. The TLS design must be confronted empirically in the evaluation of the proposal itself and the achieved learning results. In this chapter, we only will show how we evaluate the TLS itself, which is related to the quality of the design (Nieveen 2009). On the basis of collected data during the implementation, we will infer problematic aspects of the activities. Following this analysis, we will define types of students' difficulties (metacognitive difficulties, learning difficulties, related to interpretation and comprehension of information, etc.) and we will proceed to introduce modifications to the activities and their sequencing. The instruments for the iterative development of the TLS are standards instruments from the educational research such as Teacher's diary, Student's workbook and External observers' reports. In Table 13.3 shows an example redesign of an activity due to students' metacognitive difficulties. The analysis of implementation difficulties led to consider the difficulty of students to understand the objective of the activity. This type of metacognitive difficulty causes students to not adequately approach the activity, even when its objective has been explained to them (Treagust et al. 2002).

In the activity of the first version, students' standard answers when establishing the relation between current of electrons was to substitute the data in the equation $I = e\,i_e = n_e\,e\,v_d\,A$, but they do not give explanations of the meaning of each magnitude and they do not comment the result obtained, whether correct or

Table 13.3 Students' metacognitive difficulties encountered when implementing the TLS and its re-elaboration (rewriting and rethinking of the approach of the activities)

Activity 3.1 (version 1)	Activity 3.2 (version 2)	
	Microscopic point of view	Macroscopic point of view
In a copper wire, the current of electrons is about $i = 3.4 \times 10^{18}$ electrons/s. This is an incredible number of electrons to pass through a section of the wire every second. But, How long it takes for an electron traveling a meter in a copper wire? Make hypothesis: A: 10^{6} s B: 1 s C: 10^{-6} s D: Another one Suppose that 100 mA is drifting through a copper wire. The diameter of the wire is 1 mm ($A = 8 \times 10^{-7}$ m^2) and the density of mobile electrons in a copper is 8.4×10^{28} m^{-3} (a) What is the drift speed of electrons? (b) How long is a single electron in the electron sea to drift 1 m of the wire? (c) If the speed of the electrons in the wire is 9.41×10^{-6} m/s and then, electron takes 29.5 h to move 1 m. Why does the light in a football stadium come on almost instantly when you flip a switch 300 m away?	1. The velocity of the electrons in the wire in a circuit is: (a) Slow (b) Fast (c) Almost light speed Explain: 2. The force that acts on electrons is produced by: (a) E (b) ΔV (c) Other Explain:	1. The effects of the current in a circuit are: (a) Slow (b) Fast (c) Almost light speed Explain: 2. In a circuit with I current, the multimeter measures: (a) E (b) ΔV (c) Other Explain:

incorrect. However, in the activity of the second version, students have to argument about the option that they choose. Students define the meaning of the current of electrons and hypothetize about the cause of the current. The new version is more according with the learning objective LO1. The change made in the rewriting of the activity leads to students focusing on that aim when answering the questions.

13.5 Discussion

Our design-based research proposal includes common elements agreed by the community. These elements of design, implementation and evaluation allow the definition of didactic tools that help to make explicit the decisions made at the level of definition of objectives and in the design of activities to be implemented in the classroom. The TLS as a final product requires making explicit both the school context and the use of design tools, such as epistemological analysis or learning demands.

We are aware that we have only presented two examples of our design. An example of analyzing difficulties and taking them into account in the design of activities. Another example is of redesign as a consequence of implementation analysis. The objective of this chapter is not to show all the evidence obtained in the design research process, but rather to show the consensus reached by the community in the research that follows a DBR methodology and define its main characteristics. The examples try to illustrate the research theory for a specific topic.

Acknowledgment The authors would like to thank the economical support provided by the Project MINECO EDU2015-65359-P and by the Project of the University of the Basque Country GIU19/071.

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