How Physics Education Research contributes to designing teaching sequences

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Abstract
Over the last decades, a growing number of physicists have taken up the challenge of implementing the same research discipline in physics learning and teaching as applied to traditional research in the field. This commitment is widely known as “Physics Education Research” (PER). In this paper, I will single out some of the directions taken by present and emerging research that I deem promising. I will also discuss the impact of research on the educational practice of physics teaching at university level. This paper presents evidence from different studies to demonstrate the potential positive impact of research into teaching and learning physics on students’ understanding of physics. Finally, I will show some practical challenges and propose some steps that could be taken to ensure PER growth and productivity.

1. Introduction

In recent decades a growing number of physicists have taken up the challenge of applying an approach to physics education research, just as rigorous as traditional physics research, concerning problems relating to learning and teaching physics. This commitment is widely known as “Physics Education Research” (PER). PER concentrates on understanding and improving how physics is learnt by studying the contents of the physics curriculum and what teachers and students do when teaching and learning in schools. The research field relating to teaching science, and in particular Physics Education, has been well-established for some decades. It attempts to integrate knowledge from different fields of research; such as physics, the psychology of learning, the epistemology of science or the pedagogies of the teaching-learning process (Abell and Lederman 2007, McDermott 1997) in a non-mechanical way.

The objective of “improving” student learning lies at the heart of all education research. As Hurd de Hart (1991) says ‘there is a little reason to do research, unless there is a pay-off in the classroom’. PER has developed around intensifying the belief that this goal is possible. Its objective is usually formulated as “reforming or changing the teaching of physics” causing PER to go beyond identifying student learning difficulties found in traditional teaching. Research has developed didactic materials and strategies, which have been repeatedly submitted to examination, assessment and redesign. A number of different studies have had a positive impact on physics teaching and learning. One example is research into student's difficulties in terms of learning physics concepts which resulted in designing new instruments to assess students' knowledge and the effectiveness of teaching. Halloun and Hestanes (1985) used the results obtained from an investigation into university students' ideas, within the field of Mechanics, to design the “Force Concept Inventory” formative assessment test. Since its design, there has been an increase in the number of physics programmes and textbooks, which pay greater attention to conceptual differences. Recently, in the field of electromagnetism, Maloney and al. (2001) have developed formative assessment instruments with similar aims.

However, difficulties in carrying out research into teaching science, aimed at improving the practice of teaching, must not be underestimated. Lijsen and Klaassen (2004) argue that designing learning sequences requires a complex process of applying the general principles of didactics to specific teaching contexts for teaching the subjects on the curriculum. They point out that this task is not linear but rather a cyclical process with the aim of generating knowledge about teaching and learning, implementing improved teaching methods appropriately in the classroom. Designing teaching sequences is not a mechanical process involving transferring pedagogical principles and research results to teaching specific science subjects. On the contrary, teaching sequence design is a creative process, which considers not only research but also the classroom culture and the circumstances of both teachers and pupils.

In this paper I will discuss the impact of research covering educational practice of teaching physics on university courses. I will look at some practical challenges and propose some steps that could be taken to ensure PER growth and productivity.

2. Implications of P.E.R. to designing teaching sequences

Designing research-based teaching sequences takes into account two kinds of research recommendations: a) results of empirical studies on students' ideas and reasoning; b) technical contributions connected to the nature of science and how it is learnt and taught. Both contributions are connected, as the principles deriving from the latter influence how empirical studies are analysed on the former. Analysing students' ideas involve not only conceptual aspects but also epistemological and ontological aspects. On this point, it is necessary to analyse the historical development of the topic to be taught, the difficulties that the scientific community had to overcome and the arguments used to construct new concepts and explanatory models. Working from this epistemological analysis on the scientific content of school curriculum, it is possible to define the teaching-learning aims in a well-founded way. In other words, it is possible to justify choosing these aims based on epistemological evidence of the discipline and not idiosyncratically or based on the educational programme's tradition.

The research recommends sequencing the main stages that teacher must work through when designing the teaching programme. In our research group we use the so-called "learning indicators" to specify what students should learn on the topic in accordance with the school curriculum (Guisasola et al 2010). The learning indicators include ontological aspects (values and attitudes) that must be consciously taken into account. Research into teaching sciences shows that the emotional and value-related aspects cannot be considered without making a close connection to cognitive processes when students are working on their activities in science classes (Zembylas, 2005). In this respect, designing activities that relate aspects of science, technique, society and the environment to each other means supporting a presentation of socially contextualised science that encourages students' interest in the scientific topic being taught. Including activities related to Science-Technology-Society-Environment generates interest among students on the study topics, encouraging them to get involved in the solving task (Simpson and Oliver 1990).

The design and development of the research-based teaching sequences imply that creative integration must be carried out taking into account the teaching difficulties, learning indicators and ontological aspects. This creative integration leads to a close analysis of the differences between the learning difficulties and the teaching targets set in the curriculum. This analysis should build bridges between activity design and research work. In this respect we can say that we are using evidence from the empirical research when designing the sequence. It is necessary to highlight that the curriculum standards provide information on "what should be taught" generally. On the contrary, teaching aims for the panel that we have defined using the research evidence specify even further what students should learn and justify why they should do it.

Although many of the activities from the innovating educational sequences are common to the questions and exercises from the text books used in regular teaching, it is necessary to highlight that they are used differently. Maybe the most significant differences revolve around the time dedicated to student difficulties, plus activities that aim to interest the students on the topic and justify introducing new models and concepts. The sequence activities are designed with the aim of providing students with opportunities to understand and apply the same model repeatedly. On the other hand, the activities also tackle epistemological aims by getting students to appreciate the power of a scientific model capable of explaining a great number of experimental cases. As a conclusion, all the above can be organised into table 1.

Table 1. Use of research evidence to design teaching sequences

<table>
<tr><td>Students' ideas and reasoning

Difficulties in learning</td><td>Epistemological analysis of the contents of the school curriculum

Learning indicators</td><td>Interests, attitudes, values and standards

S-T-S-E Aspects</td></tr>
<tr><td colspan="3">Teaching goals

Set out specific problems and aims in a sequence</td></tr>
<tr><td colspan="3">Interactive learning environment

Teaching strategies</td></tr>
</table>

3. Teaching sequence of electromagnetic induction (EMI)

Over recent years, within the Physics Education Research Group of the University of the Basque Country (PERG-UBC), I have carried out different research projects, which have developed teaching sequences for classroom implementation and subsequent assessment as one of their main objectives. See, for example, Guisasola et al. 2010a, 2010b, 2009, 2008 and Furio et al. 2003. In this paper, I will describe the processes involved in designing teaching sequences following the instruments within chart 1, with specific reference to teaching Electromagnetic Induction (EMI) in an Introductory Physics Course at university level.

Regarding students' ideas, previous works (Guisasola et al. 2011) have identified their conceptual and epistemological difficulties in understanding the theory of EMI. On this point, it is necessary to analyse the historical development of the topic to be taught, the difficulties that the scientific community had to overcome and the arguments used to construct new concepts and explanatory models. Working from this epistemological analysis of the scientific content of the school curriculum, it is possible to define the learning indicators and justify their choice based on epistemological evidence from the discipline and not idiosyncratically or based on the tradition of the education programme. We will present the learning indicators drawn up for teaching EMI given in Table 2 below:

Table 2. Description of learning objectives and difficulties in EMI topic

<table>
<tr><th>Learning indicators</th><th>Students' difficulties</th></tr>
<tr><td>i1) Be able to weigh up how useful it is to solve the proposed problem</td><td>- EMI presentation is not significant to involve students in the study.</td></tr>
<tr><td>i2) Be familiar with the experimental phenomena of electromagnetic induction</td><td rowspan="5">- Lack of familiarity with the scientific lab methodology (compiling data, handling apparatus, analysing results)

- Difficulties to distinguish between the empirical level (use of multi-meters and interpretation of measurements) and the interpretative level that uses concepts such as variable magnetic and electric fields over time, Lorentz Force, magnetic flow and electromotive force.

- Not used to working in a group.</td></tr>
<tr><td>i.2.1) Find out about electromagnetic induction phenomena in spirals and solenoids crossed by variable magnetic fields.</td></tr>
<tr><td>i.2.2) Find out about electromagnetic induction in circuits that are moving within a stationary magnetic field.</td></tr>
<tr><td>i.2.3) Find out about electromagnetic induction phenomena caused by a combination of the aforementioned effects.</td></tr>
<tr><td>i.2.4) Be able to tell the difference between the phenomenon of producing induced electromotive force and generating induced current intensity.</td></tr>
</table>

i3) Be able to analyse electromagnetic induction phenomena qualitatively and later quantitatively. i.3.1) Using macroscopic modelling correctly i.3.2) Using microscopic modelling correctly	- Students find it hard to: a) Interpret simple induction phenomena properly. b) Attribute EMI to the presence of a variable magnetic field or to the variation of magnetic flux c) Apply Faraday's Law correctly, interpreting motional electromotive force phenomena - Students tend to use a field model more frequently than a force model when explaining EMI phenomena. - Few students show that they know how to explain the phenomena from a microscopic and macroscopic point of view
i4) Repeatedly use scientific work strategies to find the solution to the set problems.	- Lack of familiarity with the scientific methodology in problem solving. Difficulties to: o Carry out qualitative analysis o Make a hypothesis o Draw up alternative strategies o Analyse results o Handle apparatus - Not used to working in a group.

Analysing the differences between the learning difficulties and the teaching aims set provides us with bridges between sequence design and the research work. In this respect we can say that we are using evidence from the empirical research when designing the sequence. Table 3 below shows the sequence for EMI topic.

Table 3. Map of the didactic sequence for the study on EMI

Problem sequence	**Science Procedure to be learnt by the students**	**Explanations for the students to understand**
What is the interest and/or use of the EMI study?	- Science is interested in natural phenomena and their social implications. The origin of the interest in a phenomenon, situation or fact can vary depending on: the science topic, technological problems, local or global problems, etc.	- Acquiring a preliminary conception of the study that is going to be carried out and promoting interest on the EMI study.
When does an EMI phenomenon occur and when does it not?	- Make empirical observations and take down information on the phenomena that occur and make predictions on what might happen.	- Macroscopic and qualitative study of EMI. EMI occurs when there is a variable B over time and/or when a conductor moves in a magnetic field. There is no induction if the conductor is in a stationary magnetic field.
How can the EMI be quantified?	- Science is able to measure the phenomena that are seen and give quantitative answers from the phenomena seen.	Macroscopic perspective of EMI. - Faraday's Law - Induced emf - Induced emf ≠ induced I - Energy conservation law (Lenz Law)

Is there another way of measuring induced emf?	- Science can solve the same problem using different laws and points of view. A problem can be solved with different procedures and get the same results. - Find out about the field of application for the laws.	Microscopic point of view for EMI. - Lorentz Force - Magnetic force - Non conservative electric field - Relationship between emf with Lorentz force and the conservative electric field. - Reference systems and the fields.
Applications for EMI.	- The applications of science and technology in everyday life meet our needs but they are also present in our leisure. Science and its technological applications are all around us.	Know how to apply Faraday's law within the context of your everyday life beyond the school context.

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

4. Assessment of teaching sequence and conclusions

Physics education research, generating relevant knowledge about teaching science subjects, presents significant difficulties. Firstly, considering that one proposal is “better” than another involves agreeing with the aims used to assess the quality of the proposal. These quality criteria may be based on the percentage of students who pass official internal and external tests which may have some correlation with the students' results in conceptual comprehension tests. In other words, quality may be measured in terms of the number of students preparing to following science and engineering studies and in the proper preparation of this elite group. An alternative method of measuring quality revolves around how effective it is at generating better scientific literacy and increasing the wider understanding of basic scientific theories. Finally, the nature of the teaching quality is a question of values, concerning educational administration and, finally, the teachers responsible for implementing it. In any event, if different quality criteria are applied in different situations, it is not possible to identify a single “best teaching practice’.

Another important difficulty in generating knowledge relevant to teaching is demonstrated by evidence from research (Pintó 2005) showing that teachers make changes when implementing the curriculum which may affect original intentions, and envisaged goals. This may lead to teaching veering off track from its “official” goals. In addition, extensive research into teachers' thinking (Mellado 2003) shows that teachers have a positive attitude towards the results of didactic research, but are not prepared to change how they teach if the actions proposed are not consistent with their teaching practice. Teachers point out that their educational practice is strongly influenced by their school colleagues and by textbooks and didactic materials used in classroom practice.

Studies carried out by PERG-UBC bear in mind the aforementioned difficulties when analysing teaching sequence implementation. They are usually assessed in three ways. Firstly, we are interested in the effectiveness of the sequence compared to the traditional approach to teaching. Pre-test and post-test analysis is used for this, consisting of a questionnaire with questions related to the learning indicators specified for the sequence. In addition, the students' conceptual understanding in the experimental groups is compared with the Control group. These results are used to judge the sequence's effectiveness in terms of improving the students’ understanding, compared to traditional teaching of the subject. We know the methodological difficulties of making these kinds of comparisons, but we agree with Leach & Scott (2002) that if they are made in accordance with the conditions imposed by the quantitative methodology of research, they are at least as valid as any others.

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

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

Results from the Teaching and learning EMI project shows that the majority of students (between 50% and 70%) in the experimental groups demonstrate correct understanding of the studied scientific model. It would actually have been surprising if all the students had answered all the questions correctly. This would have meant that all the students had acquired all the knowledge and skills proposed in the indicators. Our, no less idealistic, intention was for the vast majority of student answers to lie between the “correct” and “incomplete” codes and this was achieved for three quarters of the pupils, in all questions. Similarly, the vast majority of the student groups, who answered tasks where it was necessary to apply the scientific model they had studied, did so correctly. In the case of control group students, the percentage of correct and incomplete replies did not reach 25% in any of the post-test questions.

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

What evidence do these results contribute to teaching the topics in question? When drawing conclusions and looking at implications for teaching, it is necessary to bear in mind that the teaching sequences designed in the different projects were implemented in two or three groups of students. In addition, teachers who implemented the sequence are experts in the teaching strategies used and have helped to design some aspects of the sequence. So, we cannot present evidence for more general contexts or teachers untrained in the use of the sequences. However, we have found that similar research on teaching sequences carried out by international groups (McDermott et al 2006, Michelini 2003) has also achieved a significant improvement in teaching the specified indicators.

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

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

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

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