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Exploring Pedagogical Content Knowledge (PCK) of Physics Teachers in a Colombian Secondary School

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Abstract: The purpose of this paper is to address the most significant contributions of pedagogical content knowledge (PCK) involved in teaching physics. Most studies have observed the characterizations of PCK via specific content in the lower secondary and upper secondary curricula. Here, we present a number of studies that show evidence for the development of some PCK components, including those that present PCK as an articulating axis for physics teacher training models. The present work is a descriptive study that analyzes, by means of a case study, the changes in PCK through a physics teacher training intervention program. This program is based on reflections about teaching, concerning the electric field in physics education. The results show that categories, such as knowledge about the curriculum and teaching strategies, evolved after the intervention program, in contrast with knowledge about evaluation and pupils. This suggests that an approach involving a teacher's reflection on what he/she designs allows for progression towards a teaching and learning process that is more focused on innovative tendencies.

Keywords: pedagogical content knowledge; physics education; teaching intervention and reflection; teaching the electric field; upper secondary education teachers

1. Introduction

Following the work of Shulman [1], there have been several fruitful studies concerning the nature, characteristics, and implications of pedagogical content knowledge (PCK) of science teachers. Most of the research, based on constructivism, showed that didactics was essential for professional training and development, although academic knowledge in science was fundamental. This knowledge was not enough, since scenarios were required in which teachers recognized and developed their PCK concerning the specific topics that were taught.

The reason that PCK has become a necessity and a general characteristic in teacher training plans [2–6] is that it allows one to: (a) identify and act on the factors that comprise and regulate the stability of teaching models; (b) validate the theoretical objects that are taught; (c) recognize how to determine the knowledge that teachers construct over the course of their practical experience; and (d) redirect the relationship between research and classroom practices [7].

Developing PCK helps novice teachers adjust their teaching, and offers experienced teachers opportunities to carry out self-regulated reflective practices [3]. According to Van Driel et al. [8], there are essential elements for the development of PCK. It is necessary, however, to keep in mind that teachers expand their PCK in particular and personal ways, depending on the content they are teaching [9].

From a different perspective, PCK is dynamic, with its own structure, sources, components, nature, and filters. In addition, PCK enables and legitimizes teaching as a profession. It is a meeting

point between a teacher's classroom practices and the knowledge acquired through training and experience [10–12].

Alonzo and Kim [10] highlight the need, when measuring PCK, to differentiate the dynamic from the static. They define dynamic PCK as related to classroom practices and the reasons underlying a teacher's decision-making during instruction; they define static PCK as related to what the teacher declares concerning teaching specific content. In this study in accordance with what was stated by Alonzo and Kim [10], PCK could be characterized on three levels: declarative, design, and action. These levels correspond to what the teacher thinks, plans, and does when teaching specific content.

Therefore, the aim of this work is to address the most significant contributions of some relevant research on PCK for teaching physics. This research concentrates on the type of domains assigned to PCK, as well as on the methods used. Finally, a descriptive study is presented, in which a particular case study is analyzed through a physics teacher's PCK, about teaching on the electric field during two consecutive courses, before and after participating in a process of innovation.

1.1. PCK in Teaching Physics

The current agenda in physics education positions PCK as a valid theoretical framework in teacher training models. It takes into account the epistemological distinctions of the base knowledge involved—knowledge of the discipline, psycho-pedagogical knowledge, knowledge of physics didactics, and knowledge of the context. In recent years, the number of investigations on PCK for the teaching of physics has increased, although it is still low compared to the existing ones for the teaching of chemistry, biology, and technology. Thus, most of the work on the PCK describe (or characterize) it from qualitative studies, and few are in charge of measuring its development—a situation that differs from studies carried out with active teachers.

Research on PCK in physics teaching covers a broad spectrum (of the lower and upper secondary physics curricula), and links studies carried out with prospective teachers and with in-service teachers, who have experience at different educational levels. As shown in Table 1, the characterization of PCK is carried out by means of its components. In some cases, PCK is considered another category of the teacher's knowledge [7,13,14], while in other cases, new ways of evaluating PCK are included (for example, Paulick et al. [15], with their introduction of academic self-concept).

In relation to the specialty of the teachers (in which PCK is characterized), the majority have a background in physics, chemistry, or mathematics. Their knowledge of pedagogy and didactics is generally focused on postgraduate programs, although there are more cases in which content and didactics are seen as integrated fields.

Most studies have used the combination of strategies and different sources of acquiring data to describe PCK, such as interviews, concept map designs, vignettes, class observations, questionnaires, and pencil-and-paper tests. Here, Kirschner et al. [16] developed the test to measure the development of PCK in prospective and in-service physics teachers. Moreover, Jang [17] implemented the test to measure PCK from students as the source. The tools developed by Loughran et al. [18] was called content representation (CoRe), and pedagogical and professional experience repertoires (PaP-eRs) have been widely used with science teachers, and the use of avatars, to simulate everyday class situations in order to develop PCK [14].

The results of the studies suggest that, in the case of content related to Newtonian mechanics, there were major deficiencies in both prospective and in-service teachers' knowledge—deficiencies that affected their selection of teaching strategies and learning objectives [19–21]. Moreover, if prospective teachers predicted their possible needs and learning difficulties, they did not use them in the teaching scenarios that were presented to them during their training process. In particular, Thompson et al. [5] found out that prospective teachers who completed a bachelor's degree in physics identified less difficulties that pupils had with electric circuits, compared to those who were not physicists. As pointed out by Bektaş [22], for content related to light and sound, prospective teachers had sufficient information on knowledge concerning the pupils, but they did not have sufficient information on effective strategies

to teach the content aforementioned, and, in general favored teaching with traditional tendencies. Brines et al. [23] indicated how to analyze the PCK of galvanic cells, and compared their prospective with in-service teachers. They concluded that in-service teachers preferred traditional (and by-discovery) methods, whereas prospective teachers used a greater variety of methods, regardless of their knowledge of the content.

Other relevant results were reported by Thompson et al. [5], who found that future teachers who had completed a degree in physics, were less likely to identify the difficulties students had concerning electrical circuits than those who were not physicists. Therefore, as Krisnert et al. [16] and Paulick et al. [15] suggests, having a high level of knowledge of the content being taught, and of pedagogical knowledge, does not guarantee having adequate PCK. Paucity of knowledge as one of the main obstacles to undertake, however, changes in pedagogical practice [23].

In general, as Etkina [2] points out, PCK offers a frame of reference for physics teacher training, reflecting what happens in class, and allows for the professional development needed for teachers to be identified.

1.2. Development of PCK

Studies describing changes in PCK conceive the process of configuring PCK as an integrative and individual process, rooted in practice [24], and needing to be guided by teaching and learning experiences through spaces for reflection, to allow encounters between theory and practice. Veal et al. [25] demonstrated two prospective secondary teachers concerning the development of PCK. They described linear motion and the micro and macro perspectives of thermodynamics, and noted the importance of taking the position that the development of PCK was complex and nonlinear.

In a case study of two primary teachers with ten years of teaching experience, Appleton [26] concluded that an increase in self-confidence concerning the content being taught, positively influences the development of PCK. De Jong and van Driel [27] and van Driel et al. [24], considering other disciplines, reinforced this idea, indicating that a lack of knowledge about the discipline being taught negatively influences the configuration of PCK. Seung et al. [28] suggested that the dilemmas teachers faced (in what they thought, planned, and did in class) constituted as main obstacles to the development of PCK.

Regarding the structure and nature of professional development programs, Appleton [26], De Jong and van Driel [27], and Hume and Berry [29] point to the role of tutoring in PCK development processes. Appleton [26] opted for individualized tutoring during planning and action, while Hume and Berry [29] interspersed individualized tutoring sessions with discussion groups. All of these authors stressed the importance of collaborative work among teachers. For example, Vázquez-Bernal et al. [30] found that collaborations with other teachers through action-inquiry could trigger the development of PCK complexification processes.

Various works have focused on describing the factors that influence the particular development of a PCK component, without implying that any particular modification will mean a general change to the whole PCK. In this regard, Orleans [31] evaluated the changes in the PCK of nine Philippine secondary school physics teachers on teaching radioactivity and nuclear energy, concluding that the greatest indicators of change corresponded to those with knowledge on the curriculum and the pupils. These changes were due to the design of a flexible professional development program, which included the teachers' interests. In the case of Henze et al. [32], the most fully developed PCK component was knowledge about teaching strategies with the factors behind its development differing in accordance from the characteristics of the starting PCK.

Most of the research connecting with the changes and development of PCK in physics teaching has focused on what teachers think and/or say they do in class, not on their actual actions in class [33]. Therefore, a pending task is to document PCK in and on actions and activities involving different content taught in physics. Thus, in this study, we describe the development of PCK with a high school physics teacher, concerning teaching on the electric field through a longitudinal study.

Table 1. Different research works of pedagogical content knowledge (PCK) on physics.

	Study	Context	Education Level	Content Analyzed	PCK Component Analyzed
PCK characterization	Johnston and Ahtee [20]	PT	Primary	Weight of the air	KC, KSC, KRIS
	Alonzo et al. [13]; Alonzo and Kim [10]	IT	Upper secondary	Geometrical optics	PCK as a category
	Bektaş [22]	PT	Lower secondary	Light and sound	KSC, KRIS, KE
	Brines et al. [23]	PT/IT	Lower secondary	Galvanic cell	OTS, KC, KSC, KRIS, KE
	Halim and Meerah [20]	PT	Lower secondary	Friction force; gas laws and changes of state	KSC, KRIS
	Jang [17]	IT	University	Relation seeing and light Thermodynamics	KC, KSC, KRIS, SMK
	Kirschner et al. [16]	PT	Secondary (lower and upper)	Mechanics (force, velocity, torque, energy)	KRIS, KSC, PK, SMK
	Lee and Luft [34]	IT	Upper secondary	Parabolic motion; Newton's laws; electromagnetism	OTS, KC, KSC, KRIS, KE, KR
	Louragh et al. [18]	IT	Upper secondary	Force, circuits	OTS, KC, KSC, KRIS, KE, KRIS; pedagogical skills
	Chini et al. [14]	PT	University	Graphics in kinematics	KSC, KRIS, PK, SMK, self-concept
PCK development	Paulick et al. [15]	PT	Lower secondary	Relativity	Metacognitive knowledge
	Yerdelen-Damar et al. [35]	PT	Secondary (lower and upper)	Different curricular contents	KRIS
	Zhou et al. [21]	PT	Secondary (lower and upper)	Newton's third law	
	Henze et al. [32]	IT	Lower secondary	Modeling—model of the universe and solar system	OTS, KC, KSC, KRIS, KE,
	Nivalainen et al. [36]	PT/IT	Lower secondary	Laboratory practices	KSC, KRIS
	Nilsson and Loughran [37]	PT	Primary	Flotation and sound	KC, KSC, KRIS, KE,
	Orleans [31]	IT	Upper secondary	Radioactivity and nuclear energy	KC, KRIS
	Sperandeo-Mineo et al. [7]	PT	Primary	Modeling—thermodynamics	PCK as a category
	Seung et al. [28]	PT	University	Matter and interactions	KC, KSC, KRIS
	Veal et al. [25]	PT	Lower secondary	Linear motion, thermodynamics	PCK taxonomies

Note: PT: prospective teacher; IT: in-service teacher; OTS: orientations to teaching science; KC: knowledge of the curriculum; KSC: knowledge of pupils' understanding of science; KRIS: knowledge of representations and instructional strategies; and KE: knowledge of evaluation.

2. Materials and Methods

The research was carried out with a secondary school physics teacher in Colombia, whom we will refer to as Isabel. When Isabel began the investigation, she was 28 years old. She had training in science teaching, worked in a private school in the city of Bogotá, and had 7 years teaching experience. Her pupil ages ranged from 17 to 19 years, and they were taught as a group of 15 to 30. The research was carried out during Isabel's first year of teaching in the upper secondary level.

The present study focuses on the characterization of PCK during two consecutive courses, before (BI) and after (AI) implementing an intervention program based on metacognitive reflection. The intervention program was designed starting from the initial PCK diagnosis. It was considered that the intervention processes with the teacher should be based on continuous, self-regulatory, and metacognitive reflection, starting from the context of everyday work and through shared knowledge-building processes.

The decision of what aspects would be worked on was agreed on together with the teacher, in accordance with her interests, using three sources. They were (a) theoretical reflections about the PCK components; (b) teacher interests and difficulties regarding teaching on the electric field and force; and (c) an overall analysis of the data, which allowed us to devise a general profile of the PCK [11]. The intervention with the teacher centered on three aspects that had previously been agreed on: (i) educational meetings; (ii) analysis together of the classroom observations, the lesson plans, the CoRe, and the interview; and (iii) preparation of the new teaching unit on the electric field. The reflection processes were raised individually. In which the study researchers worked with the participating teacher individually. For this research, it was crucial to create an environment where the teacher felt that the work they did within the investigation was recognized. An example of activity carried out during the training meetings with the teacher is presented in the annexes. The activity was

a meeting point to discuss the teacher's concept of the electric force as a continuous force, the concept of the electric and potential field, and the functionality of field lines.

The tools used in this research, as shown in Figure 1 were: (a) an open-ended questionnaire on what the teachers considered to be the strategies in physics teaching and the role of planning in the teaching and learning process; (b) the matrix (CoRe) designed by Loughran et al. [18] to represent the content; (c) the didactic unit developed by the teachers on electricity and magnetism; (d) recordings of classes; (e) a post-class-recording questionnaire; (f) a semi-structured interview to investigate the teachers' PCK on the electric field; (g) semi-structured interviews for the teacher to give her assessments of the research process; and (h) a field journal.

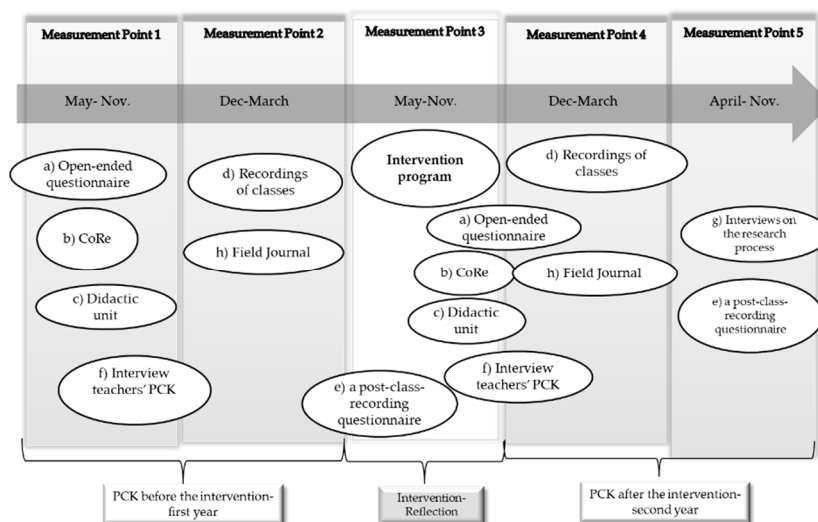


Figure 1. Tools used in this research.

For the design of the instruments a, f, g, and h, we opted for open questions since our intention was to obtain varied and broad answers without the pretense of conditioning or predisposing the participating teacher regarding teaching on the electric field and its PCK. The questions were developed based on the literature on PCK involving science teachers, and research on teaching on the electric field. These instruments were implemented in private (a place chosen by the teacher). During the interviews, the level of difficulty of the questions alternated between a descriptive nature and deeper reasoning. The responses were audio recorded and transcribed verbatim for later analysis. The instruments were evaluated by four university professors (two Spanish and two Colombian professors), experts in didactics of experimental science and teacher training, who made contributions on the writing and structure of each instrument. An example of the instruments used is in Appendix A.

The category system was developed, taking the model of Magnusson et al. [38] as a base. The categories considered were: (a) knowledge of the curriculum concerning electric fields; (b) pupils' knowledge when learning about the electric field; (c) knowledge of teaching strategies on the electric field; and (d) knowledge of evaluation for the electric field.

Each category was defined from two opposing tendencies: traditional or teacher-centered (TT), and innovative or pupil-centered (TC), with an extra intermediate tendency (TI), which included categories that might be somewhat closer to the teacher- or pupil-centered practices. To carry out this classification, the descriptions given in the teaching models for experimental science didactics it should be considered [39,40], and their overlaps with the data that were collected. In addition to this organization by tendencies, the analysis was subdivided in accordance with what teachers declared, planned, and did in their classes. The results showed the triangulation of instruments were a, b, f, g, and h; the results of the triangulation of instruments were b, c. What it did, in essence, was make up the class recordings, supported by the CoRe, the field diary, and the post-class recordings questionnaire.

In accordance with the hypothesis of progression of Porlán and Rivero [41], evolution from the traditional to the innovative tendency was considered a progression, and the contrary a regression. Moreover, the USA’s National Research Council, pupil-centered orientations, were an indicator that teaching strategies of inquiry and innovation were being implemented in classrooms. The results were presented together, to three expert researchers, to confirm the relevance and reliability of the description. The final codebook was collected by Melo et al. [42].

Finally, content analysis techniques were used to systematize the data and their analyses, which included the following steps: (a) identification of the information units from each instrument or tool used to collect the data; (b) coding of information units; (c) categorization of information units; (d) analysis of the information units; and (e) incorporation of emerging categories to the description based on the analyses carried out. The process was supported by the Nvivo-10 software package. The data were analyzed conjointly by two members of the research team on the basis of a content analysis, and subsequently by an independent researcher. The agreement rate achieved, using consults of coding comparison, was 92%. Disagreements were resolved by consensus.

3. Results

Table 2 summarizes the dominant tendencies of Isabel’s PCK before and after the intervention based on what she declared, planned, and did in her class. In each category, a dominant or present tendency was identified. The cases in which there was a presence of the three different tendencies (traditional (TT), intermediate (TI), and innovative (TC)) are represented with an O (symbolizing that there was no definite tendency), and the tree classifications appear in combination. Changes are highlighted in grey [11,42]. The results shown indicate the most outstanding aspects of each category analyzed.

Table 2. Predominant tendencies of Isabel’s PCK [11,42].

PCK Components	Categories	Declarative		Design		Action	
		BI	AI	BI	AI	BI	AI
A. Knowledge of the curriculum concerning electric fields	A1. Objectives	TC	TI	TT	O	TT	TT
	A2. Organization of the content	TT	O	TT	O	O	O
	A3. Sources and resources	TI	O	O	O	TT	TT
B. Knowledge of teaching strategies on the electric field	B1. Type of strategies and activities	TT	O	TT	O	TT	O
	B2. Teaching sequence	TT	O	TT	O	TT	O
	B3. Strategy selection criteria	TC	O	TI	O	TT	O
C. Knowledge of evaluation for the electric field	C1. Object and purpose of the evaluation	TT	TT	TT	TT	TT	TT
	C2. Type of evaluation instruments, techniques, and design	O	O	O	O	O	O
	C3. Grading	TT	TT	TT	TT	TT	TT
D. Pupils’ knowledge when learning the electric field	D1. Nature of the pupils’ ideas	TC	O	TT	O	TT	O
	D2. Learning difficulties	TT	O	TT	O	O	O
	D3. Participation	TT	TT	TT	TT	TT	TT

BI: before the intervention; AI: after the intervention; TT: traditional or teacher-centered tendency; TI: intermediate tendency; TC: innovative tendency; O: the three tendencies emerge in combination.

3.1. Knowledge of the Curriculum Concerning Electric Fields

In Isabel’s case, the PCK components that went through the greatest progression over time (from planning to action) were curricular knowledge and teaching strategy knowledge. Considering the declarative data for these same categories, however, Isabel changed from intermediate and innovative tendencies to more indefinite ones, regulating her statements after the intervention about what she planned and did in class. In general terms, Isabel went from a PCK—more focused on herself and what she planned and did—to another that was a mixture of different tendencies, and, therefore, less defined.

The teaching sequence described in her declarations and design before the intervention started from experiences related to electrification by friction and ended with the equations of field strength.

The structural thread on the concept goes from “simple” (electric charge) to “complex” (electric field) along a linear sequence (A2–TT). During classes (i.e., what she did), however, the teacher presented force as being an effect of the field, then went on to define field, and ended up with the idea of electric force, presenting aspects of the history of electrostatics (A2–O). Furthermore, the most widely used analogy was that between the magnetic and electric fields.

“Those field lines give him (referring to Faraday) the idea to think about what he later called the magnetic field around, and they allow us to understand many things in terms of interaction” (Recordings of classes, second year).

The sequence of content in which force was the effect of the field was reinforced after intervention through the recognition of the idea of field, which she projected to her pupils. We considered that the factors influencing this sequence adoption of content were the construction of a concept map during the planning process, and the reflection on the teaching strategies used. Regarding this, she declared: “[...] up to this point, I do not have enough actions that point them towards the idea of field and on the contrary quite a lot of importance is given to the mechanistic vision of action at a distance which is probably the one they most remember later despite telling them about the conditions limiting it, perhaps being able to present experiences that ratify the construction of the idea of field contributes to giving more weight to the said aspect, like the field lines with magnets” (CoRe, second year).

Thus, Isabel acknowledged that the lack of knowledge on specific sources and resources for teaching on the electric field affected the coherence between pupil-centered approaches to teaching and learning. Here, she actually put the information into practice in class, which was centered on the teacher’s presentation (A3–TT). This situation did not change after the intervention.

3.2. Knowledge of Teaching Strategies on the Electric Field

For teaching strategies, she initially declared conceptions that were close to an innovative tendency, pointing to the pupil as being the criterion for the selection of her strategy to teach electric fields (B3–TC), as shown in an example below:

“The use of different strategies, methodologies and didactics must always aim at the formation of a reflective thought, which conceives science as a knowledge under construction of its foundations and laws that should not be far from our understanding and in which we can become active participants. Achieving this position on the part of the students implies a joint effort, not only of science teachers but also of the various areas, related or not. The implementation of simple experiences bring students closer to understanding of the laws that govern the different phenomena, starting from their previous conceptions. That guides them towards a clear objective and always giving relevance to the process that led to their construction, that is, recognizing the work scientific, which can be the starting point” (Open-ended questionnaire, first year).

These ideas were not reflected, however, in the description she gave of the didactic sequence and the activities she used in class, which were more typical of the traditional tendency (B1–TT, B2–TT). After the intervention, she showed a mixture of tendencies in her selection of strategies. For example, she proposed strategies related to everyday life that allowed the pupils to move from the abstract concept to the simple concept, as shown in Table 3. She also put into practice a new teaching sequence that involved the pupils doing experiments, followed by debates for them to discuss, reason about, and validate their own results.

According to the teacher, the introduction of usual examples related to magnetic fields, such as iron filings and magnets, and their direct relationship with circuits, allowed for better understanding of the idea of field, instead of including the idea of a gravitational field and the subsequent analogy with the electric field (B1–O). The teacher’s representational amplitude, with respect to the content, suggests that there was an attempt to establish coherences between what she declared, designed, and did in class, as well as an intention to progress towards a constructivist tendency.

Table 3. Teaching sequence proposed by the planning of Isabel.

Before the Intervention		After the Intervention	
1.	Problematize the conception of electric charge, that is, answer the question, how are bodies electrified?	1.	Problematize the conception of electric charge, that is, answer the question how are bodies electrified?
2.	Introduce the idea of force and definition of Coulomb's law.	2.	Focus your gaze on the medium and introduce the electric field as a "mediator" of the interaction.
3.	Focus your gaze on the medium and introduce the electric field as a "mediator" of the interaction.	3.	Show systems that exemplify the action of a field, (for example, the case of iron filings and the magnet). Establish generalizations from what is observed.
4.	Establish the relationship between gravitational and electric field.	4.	Propose a situation of "electrical conflict", carry out Oesterd's experiment, and show the relationship between electric and magnetic forces.
5.	Define the notion of field and introduce the lines of force.	5.	Establish a relationship among actions 1, 2 and 3.
6.	Introduce the idea of electric field intensity. (Didactic unit, first year).	6.	Outline the relationship between the manifestations of current and the electrification of bodies.
		7.	Define the notion of field and introduce the lines of force, presenting the analogy with the magnetic case.
		8.	Introduce the idea of force and definition of Coulomb's law.
		9.	Introduce the idea of intensity of the electric field. (Didactic unit, second year).

3.3. Knowledge of Evaluation for the Electric Field

Regarding knowledge of evaluation for the electric field, Isabel did not show any changes in the evaluation components during the two years of the study. In what she declared and her practice in class, she used an evaluation to measure and verify what her pupils had learned with the explanations she had given them. She only valued the recognition or evocation of definitions, and the correct execution of the exercises the pupils were set (C1–TT). Regarding this intervention, the teacher said: "I have kept the presentation of the concept of field related to that of electric force and therefore of charge. Although greater emphasis has been given to the conceptual construction and the representational aspect, the presentation of the operational definition of the concepts of force and field is kept, and likewise the evaluation is still carried out around these three aspects: understanding, explanation, and application of the concept, its vector representation, and the adequate use of its operational definition" (CoRe, second year).

Besides, Isabel pointed out that she had been implementing the same evaluation routines for many years, so the means and formats remained the same, year-after-year, despite her other established intentions for teaching. She was aware that the correct resolution of the question did not provide definitive evidence about a pupil's learning, although it was one of the tools she most used in her teaching, but not the only one (C2–O). The category referring to grading was the one that Isabel least discussed. In all of the areas analyzed, there was the suggestion that it had a comparative and discriminatory function (C3–TT). She accepted that the grading was set by the school and was shared by the rest of the school's science teachers, and, therefore, was not an element for discussion.

3.4. Pupils' Knowledge When Learning the Electric Field

What Isabel initially declared revealed that her concepts had been close to an innovative tendency, highlighting the active role that her pupils played in the learning process about electric fields (D1–TC). These ideas, however, were not carried over to her design and action in which pupils were considered to lack the knowledge and level of reasoning required to take up the idea of electric fields (D1–TT).

It could be presumed that the change from a traditional tendency to a mixture of tendencies manifested after the intervention (Table 2), due to her statements being based on the evidence of the actions carried out during the first year. However, it was not an overall requirement, and considerations about teaching upper secondary school physics. The change was also due to the widening of her

knowledge about the difficulties of learning about electric charge, force, and fields. From what she declared and designed before the intervention, Isabel believed that the learning difficulties (difference between electric force and field, charge as energy, and the concept of force) came mostly from the results of written examinations (D2-TT). After the intervention, the teacher completely changed her point of view, identifying new difficulties and predicting others, and sometimes describing what caused them, which corresponded to a mixture of tendencies as the examples showed:

“The pupils’ ideas are hard to identify, especially now, when you expect me to define field for the new unit, because I do not know how to do this” (Field Journal, first year).

“What is the case is that one may introduce, or not, the concept of field through the analogy with gravitational field? Then, that analogy with the gravitational field well I do not know and I had not thought about it, sometimes the idea of gravitational field does generate difficulty then the idea of field also generates difficulty for the pupils, because they do not see it and sometimes they set themselves to think about it” (semi-structured interviews on PCK, second year).

Finally, regarding participation, the teacher considered that the pupils who participated in class were the only ones involved in the process of configuring the explanations (D3-T).

4. Discussion and Conclusions

The characterization of PCK is a complex exercise that, in the case of teaching physics in secondary school, and especially in upper secondary, requires greater documentation and research if it is included in teacher training programs. We also observed the multiplicity of methods used to characterize this type of knowledge and, the existence of a great diversity of positions with respect to the nature of PCK.

With PCK considered to be the center of professional knowledge, its development has taken on an important role in the processes of teacher training and professional development. Research studies explicitly demand its presence in teacher training programs; thus, the relationship between the processes of teaching and learning, which ontologically depend on each other, are approached from different areas of knowledge [4]. Therefore, the design and implementation of intervention programs should become the most relevant aspect to achieve a didactic change. To achieve this goal, these efforts should be complemented with a deep analysis of classroom practices that are based on the theoretical aspects of PCK, endowing the teacher’s know-how, planning, and form of action with a more reflective character. Although the task of developing PCK was not easy, it is important to mention that each teacher had a unique PCK profile, which was constantly changing, and, therefore, each PCK profile could be constructed differently [3]. Isabel is a clear example.

Regarding the objective of the study, the results show that the progression in each component of Isabel’s PCK was not always in the same direction, be it from a traditional tendency, innovative, or vice versa. The emergence of the mixed category between these tendencies (O) is a reflection of this fact. This new category represents a possible change in which the teacher selects aspects of the traditional, intermediate, or innovative tendency to organize her teaching of the content in question, rather than positioning herself distinctly in another tendency [42].

Isabel’s PCK, considered from her planning perspective, became more elaborate as she, (a) acquired greater confidence with the content she was teaching (and greater comprehension of the contexts of teaching); (b) revised her teaching practices; and (c) created new forms of didactic representation. There was no causal and direct repercussion, however, of changes in the curricular component and her teaching strategies on some aspects of the pupils’ learning (regarding the electric field). On the contrary, Park and Chen [43] already pointed out that the PCK constructions were largely influenced by the interaction of their components. Aydin et al. [44] pointed out how the relationships between the PCK components of novice teachers were often fragmented, and showed how through practice they can become more coherent.

Our results demonstrate the strong resistance to change in what the teacher does in class against what she declares and plans, and the need for a physics teacher’s training and development programs to strengthen the teachers’ knowledge. In general terms, Isabel’s changes, in the emphasis of each

tendency, were due to how she organized the content she was teaching. The flexibility provided by this new organization of content allowed her to intervene in the organization of her teaching and in the type of strategies she selected for teaching. It also had an impact on the statements she made concerning her pupils' learning.

Several studies support the results obtained. Ogan-Bekiroglu [45] reported the few changes teachers declared—they noted that how they evaluated was due to self-efficacy about their ability to evaluate others, and to their knowledge of effective evaluation methods [46,47]. This fact highlights the need to assess the role that this knowledge plays in the training and professional development processes of physics teachers. Moreover, we concur with Van Driel et al. [8] that any process of teacher training and evolution of PCK should not be done in abstract, but with specific content.

Finally, the results also suggest that a subsequent intervention program should focus more on such aspects as knowledge on evaluation and the obstacles and facilitators of change between what was designed and what was actually done in class.

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Appendix A

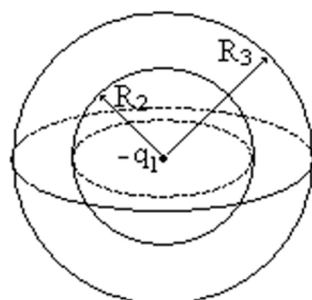
English Version—Example Activity Developed during the Intervention

As we progress in the intervention, we detect our own difficulties regarding the teacher's conceptions related to the electric force as a continuous force, and the idea of force at a distance, the concept of the electric field, potential, polarization and induction, and the functionality of power lines. To discuss these aspects, we proposed the following activity:

All Electrostatics Can Be Explained with Coulomb's Law and Biot and Savart's Law

Situation 1: the concepts of electric and magnetic fields are taught as mere mathematical resources. The electric field is usually presented as the quotient of the electric force by Coulomb's law. This is one of the causes of the low performance of students in electrostatics. There are electrostatic situations in which the application of the field concept is essential, if the phenomenology imprinted on the situation to be solved is to be explained. However, concerning what privileges from the teaching strategies that are taught is the opposite. The concept is usually dispensed with, or the student is led to not see the need for its use. Its function is confined as an expression with a decontextualized algorithmic sense of reality. What do you think about it? What are the situations in electrostatics where the field concept is essential?

Situation 2: A charged particle $-q_1$ is placed in the center of two concentric conducting spheres of radii R_2 and R_3 . None of the conducting spheres have been previously charged.



A student makes the following statement: “The field is zero anywhere outside the inner sphere because the inner conducting sphere blocks the electric field of $-q_1$. Thus, the outer sphere has no charge on its surface” [48].

Do you agree with the statement? Explain.

Interview about the Pedagogical Content Knowledge on the Electric Field

Introduction—Vision and Purposes on the Teaching of Sciences

- Describe to me what a class would be like, centered on the students and another centered on the teacher.
- What is your role and your students’ role during your physics classes?
- What advice do you give your students to improve their learning towards physics?
- What is the role of the experiment in physics? What is its role in teaching?
- What is the relationship between physics and mathematics?

A. Knowledge about the Curriculum

- What criteria do you use to plan and run your electrostatics and electric field classes?
- What are the central ideas that need to be taught to promote effective learning about the electric field?
- Have you established any relationship between the subject of electric field and other contents of physics or other areas? Which ones?
- What resources and sources are essential for you during the teaching of the electric field?
- Do you think there is coordination between science subjects? Between physics and mathematics?
- What does knowing/learning about the electric field contribute to your students?

B. Knowledge of Strategies

- Tell me a little about how you have structured your electrostatics classes. Can you tell me which teaching sequences you use? What criteria did you use to propose them?
- What actions do you implement to reinforce an idea that you consider important?
- Do you establish some actions to motivate your students to learn about the electric field? Which ones?
- What analogies, activities, examples do you consider essential to arrive at an understanding of the electric field?

C. Knowledge of the Evaluation

- What evaluation is useful for? Which one is for your students?
- How do you identify what your students have learned about the electric field?
- What should be evaluated about the electric field?
- How do your students react to the evaluation you propose?
- What things do you take into account when planning an electrostatics evaluation? How do you define its level of difficulty?
- How do you evaluate the effectiveness of your teaching?

D. Knowledge of Students

- What do you need to know about your students to help them improve their learning about the electric field?
- What difficulties do your students have when they learn about the electric field? What are the reasons for these difficulties? What have you done about it?
- Do you think that during your classes the ideas of the students on the subject of study are changing? How do you record this?

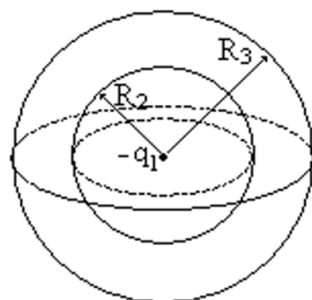
Spanish Version—Ejemplo Actividad Desarrollada durante la Intervención

A medida que avanzamos en la intervención detectamos dificultades propias sobre las concepciones de los profesores relacionadas con la fuerza eléctrica como fuerza continua y la idea de fuerza a distancia, el concepto de campo eléctrico, potencial, polarización e inducción y la funcionalidad de las líneas de campo. Para discutir estos aspectos propusimos la siguiente actividad:

Toda la Electrostática se Puede Explicar con la Ley de Coulomb y la Ley de Biot y Savart

Situación 1: Los conceptos de campo eléctrico y magnético son enseñados como meros recursos matemáticos. El campo eléctrico suele presentarse como el cociente de la fuerza eléctrica por la ley de Coulomb. Esta es una de las causas del bajo rendimientos de los estudiantes en electrostática. Hay situaciones electrostáticas en las cuáles la aplicación del concepto de campo es imprescindible, si se quiere explicar la fenomenología impresa en la situación a resolver. Sin embargo lo que privilegia desde las estrategias de enseñanza que se enseñan es lo contrario. Se suele prescindir del concepto, o se lleva al estudiante a no ver la necesidad de su uso. Se confina su función como una expresión con sentido algorítmico descontextualizado de la realidad. ¿Qué opinas al respecto?, ¿Cuáles son las situaciones en electrostática donde el concepto de campo es imprescindible?

Situación 2: Una partícula cargada $-q_1$ se coloca en el centro de dos esferas conductoras concéntricas de radios R_2 y R_3 Ninguna de las esferas conductoras han sido cargadas previamente.



Un estudiante hace la siguiente afirmación: “El campo es cero en cualquier lugar fuera de la esfera interior porque la esfera conductora interior bloquea el campo eléctrico de $-q_1$. Así, la esfera exterior no tiene carga en su superficie” [48].

¿Estás de acuerdo con la afirmación? Explica.

Interview about the Pedagogical Content Knowledge on the Electric Field

Introducción—Visión y Propósitos sobre la Enseñanza de las Ciencias

- Describeme como sería una clase, centrada en los estudiantes y otra centrada en el profesor.
 - ¿Cuál es tu papel y el de tus estudiantes durante tus clases de física?
 - ¿Qué consejos das a tus estudiantes para mejorar en su aprendizaje hacia la física?
 - ¿Qué función cumple el experimento en la física?, ¿Cuál es su función en la enseñanza?
 - ¿Qué relación mantiene la física y a las matemáticas?
- A. Conocimiento sobre el Currículo
- ¿Qué criterios utilizas para planificar y ejecutar tus clases de electrostática, del campo eléctrico?
 - ¿Cuáles son las ideas centrales que deben enseñarse para propiciar un aprendizaje efectivo sobre el campo eléctrico?
 - ¿Has establecido alguna relación entre el tema campo eléctrico y otros contenidos de física o de otras áreas?, ¿cuáles?
 - ¿Qué recursos y fuentes son para ti indispensables durante la enseñanza del campo eléctrico?
 - ¿Consideras que hay coordinación entre las asignaturas de ciencia?, ¿entre física y matemáticas?
 - ¿Qué les aporta a tus estudiantes conocer/aprender sobre el campo eléctrico?

B. Conocimiento de las Estrategias

- Háblame un poco sobre cómo has estructurado tus clases de electrostática ¿Puedes decirme que secuencias de enseñanza utilizas?, ¿qué criterios utilizaste para proponerlas?
- ¿Qué acciones implementas para reforzar una idea que consideras importante?
- ¿Estableces algunas acciones para motivar a tus estudiantes a aprender sobre el campo eléctrico?, ¿cuáles?
- ¿Qué analogías, actividades, ejemplos consideras esenciales para llegar a una comprensión del campo eléctrico?

C. Conocimiento de la Evaluación

- ¿Para qué te sirve la evaluación? ¿para qué les sirve a tus estudiantes?
- ¿Cómo identificas lo que tus estudiantes han aprendido sobre el campo eléctrico?
- ¿Qué se debe evaluar sobre el campo eléctrico?
- ¿Cómo reaccionan tus estudiantes frente a la evaluación que propones?
- ¿Qué cosas tienes en cuenta cuando planificas una evaluación de electrostática?, ¿cómo defines su nivel de dificultad?
- ¿Cómo evalúas la efectividad de tu enseñanza?

D. Conocimiento de los Estudiantes

- ¿Qué necesitas saber sobre tus estudiantes para ayudarlos a mejorar su aprendizaje sobre el campo eléctrico?
- ¿Qué dificultades tienen tus estudiantes cuando aprenden sobre el campo eléctrico? ¿a qué se deben estas dificultades? ¿qué has hecho al respecto?
- ¿Consideras que durante tus clases las ideas de los estudiantes sobre el tema de estudio van cambiando? ¿cómo registras esto?

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