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Sustainable Change in Primary Science Education: From Transmissive to Guided Inquiry-Based Teaching

Carolina Nicolás-Castellano [1,*], Rubén Limiñana [1,2], Asunción Menargues [1,2], Sergio Rosa-Cintas [1,2] and Joaquín Martínez-Torregrosa [1,2,*]

[1] Department of General and Specific Didactics, Faculty of Education, University of Alicante, 03080 Alicante, Spain; ruben.lm@ua.es (R.L.); a.menargues@ua.es (A.M.); sergio.rosacintas@ua.es (S.R.-C.)
[2] University Institute of Physics Applied to Science and Technology, University of Alicante, 03080 Alicante, Spain
* Correspondence: carolina.nicolas@ua.es (C.N.-C.); joaquin.martinez@ua.es (J.M.-T.)

Abstract: Here, we present a professional development plan to achieve lasting and coherent change in science education, from conventional teaching to guided inquiry-based teaching, covering the entire primary stage. This plan is based on a review of the literature on professional development programs and on the theory of critical mass for the achievement of complex social changes. We justify the different phases of the plan with empirical indicators to assess its success. We show the results obtained in a primary school from teachers, the principal, and families. These results, together with those obtained by the students, show the success of the plan and make it possible to identify crucial aspects to achieve sustainable changes in science teaching at the primary stage.

Keywords: guided inquiry-based science education; primary science education; didactic change; critical mass theory; sustainable change

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1. Introduction

There is a broad consensus that, at all levels of education, science should be taught in a similar way to how science is performed: following a process of (re)construction of scientific knowledge in an appropriate inquiry environment for every school level [1–3]. This orientation is addressed in the recommendations and curricula of the European Union Organisms [4,5] and the USA [6,7].

In this way, the current Spanish curricula establishes that Natural Sciences in elementary school must be taught in an environment that favours, among other actions, the formulation of questions, data analysis and discussion, and the construction of models [8]. From this perspective, science should be taught in a problem-based tentative environment where 'teams of novice researchers' (the students), led by an expert researcher (the teacher), address problems of interest in an open-ended way, addressing both methodological aspects and knowledge attainment [9–11]. This methodology offers repeated opportunities for students to achieve a better understanding of the scientific content because they connect concepts and ideas with phenomena that occur in their daily lives with the development of scientific skills and criteria [12,13]. In fact, different studies have shown that inquiry-based teaching has a significantly positive influence on early childhood and elementary school students' learning compared to traditional teaching (see, e.g., [12,14–17]). Moreover, it does not only lead to better learning outcomes, but also improves students' attitudes towards science [18], and therefore it contributes to achieving Sustainable Development Goal 4 (SDG 4; quality education) in the 2030 Agenda for Sustainable Development [19], which aims to increase the number of young people with the necessary skills to access employment, decent work, and entrepreneurship. These competences include scientific skills and knowledge to be able to respond to current social problems.

To teach in this way, it is necessary to have elementary teachers who have the necessary scientific knowledge and skills to act as guides and supporters during these processes. However, different studies (see, e.g., [20]) have shown the difficulties that elementary in-service teachers have when teaching science using an inquiry-based (or problematised) methodology. In Spain, most elementary teachers are generalists, that is to say, they teach several subjects, including language, mathematics, social studies, and science. Hence, elementary teachers require many areas of mastery, but they lack both sufficient coursework and experience that would contribute to their scientific knowledge background. This is necessary to help children develop a progressive and coherent knowledge of some science concepts, models, and practices and thus become scientifically literate citizens. Given their lack of knowledge (and understanding) to explain the phenomena of the world around them, it is not surprising that many teachers feel insecurity, lack of confidence, and attitudes of rejection towards science teaching [21,22].Therefore, teachers end up relying on textbooks that basically set definitions (in many cases, with misconceptions) together with 'standard' exercises without taking into account students' ideas that are substantive to work on in order for them to learn [23].

According to Davis [24], there are three important challenges faced by teachers. First, teachers' content knowledge is related to their scientific background (p. 622). Second, many teachers "have little understanding of inquiry and related skills, although, of course, individuals vary" (p. 616). And third, relatively little work had been performed on scientific inquiry carried out by in-service teachers, and "some studies investigating pre-service teachers' knowledge of scientific processes or thinking skills indicate that pre-service teachers' knowledge would be inadequate to prepare them to teach through scientific inquiry" (p. 617).

Thus, in many cases, science teaching as verbal transmission of contents in their final state continues to be the most widespread methodology in our country (and in the rest of the European countries; [25]). Given this situation, science education researchers generally think "our formal education institutions do not help students learn science with understanding" [26]. In this sense, an international science assessment (TIMSS) found that only 32% of 9-year-old students reached a high benchmark level [27]. On the other hand, a study entitled "The challenge of STEM vocations" [28] points to all of the above as causes for the loss of interest in science from early ages, which is often related to the fact that the number of students enrolled in scientific-technological careers has fallen by 28%, despite the growing demand for professionals with these profiles. These results highlight the importance of assisting teachers to learn how to support pupils scientific work.

To reverse this situation and provide a "solution" to one of the major problems for decades, so-called "professional development programmes" emerged in Spain and Europe (as it is well known that changes in educational models are closely related to the training received by teachers [24,29]). These programmes have been developed on two fronts: with pre-service teachers, current undergraduates working on university degrees that qualify them for the profession; and with in-service teachers, those who are currently teaching at school. For practical reasons, there is much more research on the first group, as researchers are mostly university teachers [30,31]. However, due to the limited time devoted to science teaching in university education (only 5–7% of the credits in the Spanish curricula), the initial training received is unlikely to influence subsequent professional practice [32]. Instead, we should consider how "professional practice" can influence initial training. In other words, if we want to improve science teaching and learning at primary schools, we should generate teachers who are role models for future teachers. Moreover, we know that in-service teacher training has the potential to bring about considerable didactic change and to improve children's learning and attitudes, as teachers can test with their own and their peer students the improvements generated by the change in the way they act [33]. Thus, given its importance, in this paper we will focus on how to introduce inquiry science teaching into professional practice at school.

In this way, many studies have analysed the impact of a particular training programme on teachers' science competences [34–37]. However, we do not know to what extent these training courses have led to real and lasting (sustainable) changes in the teaching practices of the teachers involved. On the other hand, we also find works that review and collect the conclusions obtained in these studies to determine what characteristics professional development programmes should have in order to favour the change in science teaching [38–41]. However, despite these characteristics being known, many studies show that didactic research continues to have little impact on educational practice because the results are not incorporated into school teaching [42,43]. In this sense, there is a comprehensive body of findings on approaches or features that support effective 'one-off' change in teacher practice, but little is known about how to implement these features to enable primary teachers at a school to successfully implement inquiry science teaching in a sustainable way (beyond a specific training course).

Given this background, our study aimed at the following:

(a) To conduct an in-depth review of the educational literature on effective characteristics to achieve didactic/professional change and use it, together with the theory of critical mass for changing social conventions [44–46], to design a professional development programme (genuine from this research), arranged in phases that could be assessed by means of empirical indicators of success or failure;
(b) To implement the designed programme at a primary school (case study), whose characteristics, conditions, and actions could be followed and studied in depth in order to determine which interventions facilitate (or not) the desired didactic change.

Therefore, the research questions were as follows: can we devise a plan for inquiry-based science teaching to become the usual way to teach science at a primary school? What interventions and factors facilitate sustainable change in primary science teaching? What obstacles need to be overcome? How can we evaluate the effectiveness of the plan so we can learn for future editions and scale up?

Effective Features for Professional Development in Science Education

Decades ago, professional development programmes emerged to help teachers incorporate scientific practices into their classrooms and overcome some of their limitations [1]. Now, we have reviews that highlight the characteristics that in-service teacher training programmes should have to be effective and of high quality. Firstly, there is a broad consensus that all training programmes must address the difficulties that may arise throughout the change process for the teachers involved because they will determine, to a large extent, the success or failure of the change process. Some of the 'obstacles' that appear are the following [10,41]: (a) Change takes time (years) and persistence because, at the beginning of this process, teachers have difficulties and frustration when trying to develop new behaviours and introduce new activities and materials; (b) most systems and institutions are reluctant to change (including teachers) because change is complex and it requires work; (c) teachers need ongoing support and help to change (university-school relationship); and (d) change efforts are effective when change and support are clearly defined and based on specific activities (to provide examples to be used).

The literature cites "lack of ongoing support and follow-up over time" as one of the main shortcomings of training courses [47]. Therefore, if we want to improve science teaching, we need to engage teachers beyond the duration of face-to-face training courses. According to the didactic literature, the key to doing this is to establish a lasting link over time between the researchers' team and the teachers' team [48]. To achieve this, the two teams must be involved and jointly overcome the fears and concerns that arise during the change process [49].

Secondly, this collaboration should be well-defined and based on activities with specific examples (topic-specific teaching sequences) that help teachers understand what is necessary to carry out inquiry-based science teaching in primary education classrooms [47]. If we develop specific examples of sequences with teachers (practice-connected learning), it

will enable them both to improve their scientific knowledge on the topic (better understanding of a particular topic) and to learn how to develop it in the classroom (methodological knowledge [10]). In this sense, there are studies that show that training processes that are based on the treatment of general ideas/propositions (i.e., providing general information, for example, on how to organise the classroom or how to develop scientific models) are not very useful for teachers, so that they end up abandoning the training they have received [50]. In such cases, they feel that they are constantly being told what to do, but they do not have enough help and tools to be able to transfer it into the classroom [40,51].

Of course, this requires investing the necessary time for the teachers involved to take ownership of the contents and materials so they can feel confident and able to carry out the teaching sequences. Regarding this, examples of successful training programmes are those in which the researchers' team and the teachers' team devote many hours together to intensive work seminars, continued by follow-up sessions throughout the academic year [52,53]. Moreover, such training needs to be connected to teachers' daily practice in their classrooms, so they must have enough opportunities to develop inquiry-based sequences. Teachers must learn in, from, and for practice [54]. The results of the study by Roth et al. [52] showed that the analysis of videotaped lessons was very helpful in engaging them on how to improve their intervention [10,55] and thus on feeling increasingly confident and secure in the face of change.

On the other hand, according to Schmidt et al. [56], designing a training plan with primary teachers requires curricular coherence, which is achieved by treating science teaching and learning as a progression on a structuring problem, where pupils and teachers (re)construct the most important ideas of each topic and relate them to other sequences proposed for the remaining primary school levels. When designing the teaching/learning storyline, it must be decided which guiding goals are critical within each topic and how these learning objectives need to be sequenced to be coherent. Such a progression organises concepts from near (in the early primary grades) to deep and broad (in the later years of primary school). Testing these teaching sequences in classrooms can provide the evidence needed to show teachers that in-depth teaching (rather than treating many topics superficially) achieves a substantial improvement in scientific literacy [23]. This is a fundamental point: during this process, teachers need evidence that their efforts result in better learning outcomes and attitudes of the students. If teachers spend much time and effort and results are not as expected, this will be one of the reasons for programme failure [37–39,41]. Therefore, according to the literature, the abovementioned characteristics are the most important ones for effective in-service teacher education programmes.

However, according to one of the most cited models of professional development, the interconnected model [57], it is not enough that some of these characteristics (called 'domains') are present, but connections between them are very important for the change to take place. An example of these desired connections occurs when the teacher carries out the innovation in his/her classroom ("practice domain"). Then, he/she obtains good learning outcomes (which will activate the "results domain"), which impact the general satisfaction of the families and principal team with the change ("external domain"), and, consequently, the teacher feels satisfied with his/her work and he/she wants to keep on working this way ("personal domain"). It is evident that activation of all the domains will produce a change in this teacher, and hence, the training plan would have been effective and successful. However, one thing is that the training programme had been successful at a specific moment in time, and another thing is how to ensure that this change remains in the practice of the teacher and the school, or "teachers' team", over time (i.e., to be sustainable).

In this regard, in addition to all the considerations described above, the findings of Centola should be taken into account [44]. Complex changes do not spread like viruses. This author has shown the importance of getting committed minorities to change social conventions on a large scale, so that for a given complex behaviour to spread, a minimum percentage of the population must be convinced, which is around 25%. Once this percentage is reached, the attitude and motivation of the committed minority can influence the rest,

with long-term effects. Applying this principle to a school would imply that a science training programme on inquiry-based teaching would be effective if it can get around a quarter of the school's teachers to successfully implement problem-based sequences that would improve students' learning and attitudes. Therefore, if a critical mass of committed science teachers is generated at a school who feel rewarded for their efforts, such a model will eventually spread to a large majority of science teachers at that school, and it will become the usual way science is taught. This will be the ultimate goal of our strategy for didactic change. Therefore, based on the above, we present below the professional development programme that we have designed to try to achieve this didactic change in an effective and sustainable way, based on the didactic literature and on the theory of critical mass for the change of social conventions [44,45].

2. Materials and Methods

We wanted to achieve, through collaboration between the researchers' team and the teachers and principal team of a primary school, teaching science based on the model of teaching by inquiry aligned with the Spanish curricula and NGSS. Because this is a complex problem, in order to learn and draw conclusions, it is necessary to focus the research on the analysis of cases (understanding as such the study of a school or a group of teachers whose characteristics, conditioning factors, and actions can be tracked and analysed) and to operatively define (a) What we want to achieve; (b) The plan foreseen for its achievement, arranged in phases that can be analysed; (c) How to assess the development of the plan; and (d) When it will be considered that an effective and sustainable didactic change has been achieved at that school.

2.1. A Professional Development Programme to Achieve the Science Teaching Change: Procedure and Instruments

We divided the programme into the following general phases (see Figure 1): (1) Setting the base for the change: mutual accords, initial training, and getting out possible troubles and fears towards the change, (2) First-time teaching sequence implementation by teachers (video recording), (3) Reflection seminars on the practice and implementation of the teaching sequence for the second time by teachers, (4) Achievement of lasting and extensive science teaching change. Quantitative and qualitative indicators of success were used to assess the consecution of these phases. We present here the instruments used for this assessment.

2.1.1. Phase 1: Setting the Base for the Change: Mutual Accords, Initial Training, and Getting Out Possible Troubles and Fears towards the Change

We had experience with teacher training courses convened by teacher centres. In these courses, teachers from different schools and with different motivations (to assist, a minimum number of hours is compulsory for improving their salary) signed up, but when they returned to their workplaces, they generally did not put into practice what was dealt with within the course. They felt isolated, without the necessary social support for the change. However, the change from transmissive to guided inquiry-based science teaching is very complex. It requires social groups of people with "strong and redundant ties" [45,46].

Therefore, we directed our research to how to have science teaching changed in a school. In this context, the probability of finding groups of people with similar circumstances and strong and redundant ties—all of the factors that favour spreading changes—is high. In this first phase, we wanted to achieve (1) a trusting and collaborative environment during and after developing the teaching sequences in an intensive course; (2) knowing the teachers' difficulties in developing the implementation; and (3) obtaining the willingness and commitment of some of them (a number close to or higher than the critical mass) to initiate the change in their classrooms.

We designed a course and also the sequences of activities so the interested teachers could put inquiry-based science teaching sequences (onwards, IBSTS) into practice after

the training course [40,58]. The seminar took place in a problematised environment, where each teaching sequence started with structuring questions or problems that were appropriate for each grade level. This sequence also represents a progressive advance in the core problem or idea chosen, from 1st to 6th grade [10] (in Spain, 6th grade belongs to primary, not middle school). Teachers, organised in small groups, can experience the learning environment generated. Those small groups developed the IBSTS, led by one member of the research team. When developing every sequence of activities, in the sharing, opportunities were reiterated for the teachers' ideas to emerge, which were analysed, advancing, in a tentative environment, in the justified response to the problem or question raised at the beginning. The end of the course was a good moment to ask teachers about their concerns and difficulties in implementing the innovation (to help teachers overcome them in the following phases [54]).

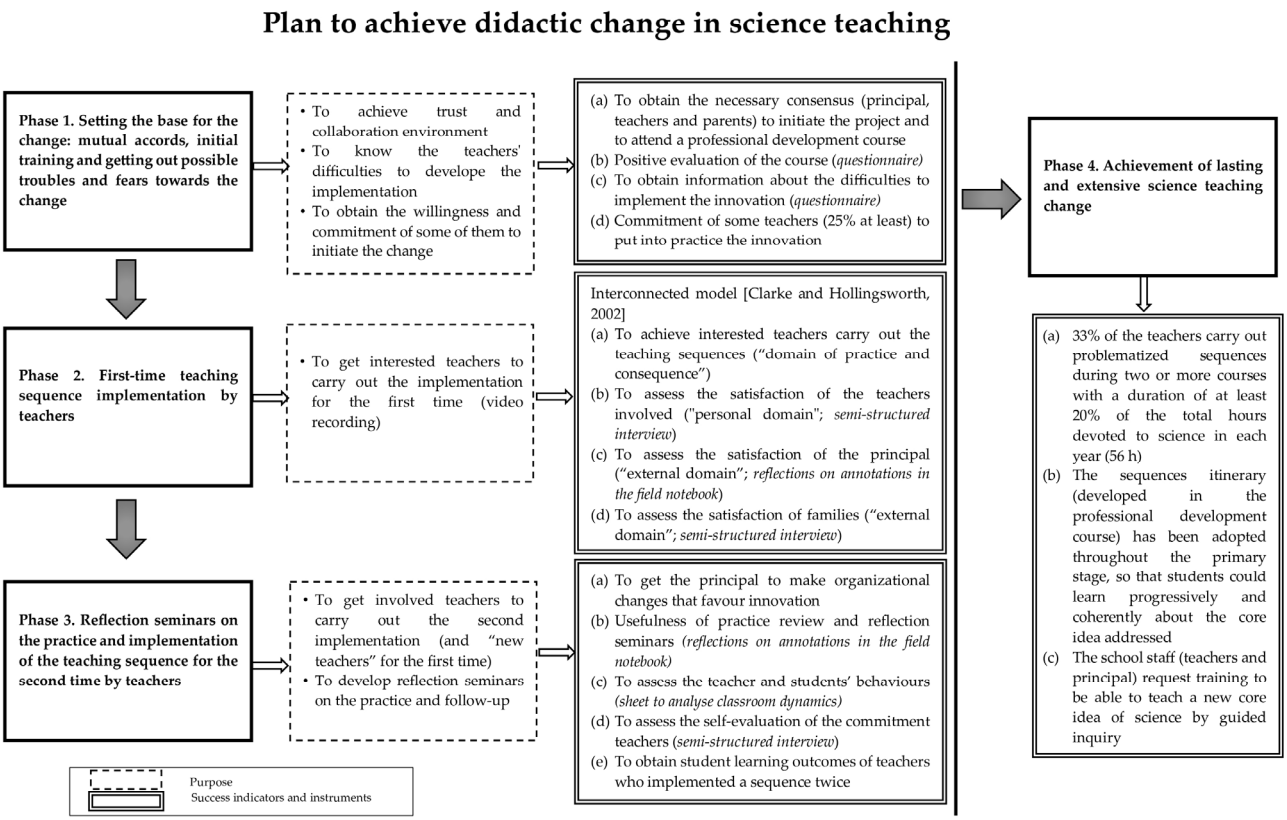

Figure 1. Diagram of the phases of the plan, indicating the purpose, success indicators, and instruments for every phase [57].

Success Indicators and Instruments

To determine the success of this phase, we took into account the following indicators:

- Obtaining the necessary consensus (principal, teachers, and families) to initiate our change project and therefore carrying out an intensive training course with interested teachers. This consensus included that the teachers had to be volunteers, the families had to be informed, the principal had to favour possible changes in schedules, and the confidentiality of the data obtained (videos, student results, etc.) would be protected by contract with the legal service of our university.
- Positive evaluation of the training course and usefulness of the obtained information "in the field" on the difficulties and needs that teachers may have to carry out the innovation. To evaluate these aspects, we designed a questionnaire made up of two sections: the first was a list of statements about different aspects of the course (teachers, interest in the contents, knowledge acquired, etc.) to be scored using a Likert

scale from one to five (1 = very negative; 5 = very positive). In the second section, participants were asked about possible difficulties in putting into practice some of the IBSTS of the course and their willingness to do so. To obtain this information, we set two questions: the first asked about the origin of the difficulties they would have in putting into practice some of the sequences, and the second question was identical but referred to other colleagues (who did not participate in the course). Thus, by personalizing and depersonalizing the questions, we hoped to obtain more reliable information about the real difficulties. The end of this course was an appropriate time to collect this information because teachers were more aware of what is required to implement an IBSTS. The analysis of the second part of the questionnaire (on difficulties) was carried out by two of the authors of this article. Previously, they established categories (difficulties) that they thought were likely to appear, including an open category for unforeseen responses, and reviewed all the questionnaires separately to categorize the responses. Subsequently, they compared their analyses and discussed the discrepancies they observed. In cases of agreement, we established a 1, and in cases of disagreement, a 2. With this, we calculated Cohen's Kappa coefficient, and we obtained an agreement rate greater than 90%. Finally, they agreed to establish the following six categories: lack of personal involvement, lack of scientific knowledge, influence of the physical environment, lack of time, lack of material resources, and lack of training. The questionnaire was individual and anonymous (see Appendix A). The questionnaire was subjected to expert judgement for content validation (for more details, see [59]).

- Commitment of some teachers (25% at least) to put into practice some of the teaching sequences developed and to be videorecorded, with an approximate duration of ten teaching hours.

2.1.2. Phase 2: First-Time Teaching Sequence Implementation by Teachers (Video Recording)

This phase requires a lot of time and effort (for both teams), and it is therefore one of the most decisive phases for the continuity of the project. The committed teachers are confronted with change for the first time. This requires a process of "ownership", which demands personal work (a lot of attitudinal involvement) [60,61]. Achieving the didactic change has less to do with convincing people that the idea is good than with the challenge of getting them to do the extra work required to put it into practice [45] (p. 137). Indeed, as we have mentioned before, teachers need a lot of support to implement the IBSTS for the first time [50,62]. For this reason, our team assisted committed teachers by developing seminars to review and reflect again on IBSTS and to prepare the materials. In addition, the research team provided support during all sessions of their intervention, which were video recorded for further reflection on the practice. We also measured the learning and attitudes of their students; we informed teachers that the measurement of results would only serve to document the process and that they would only be used for internal analysis for further improvement [10,47]. Knowledge attainment will be reliable when they have owned the sequence, which, as a reasonable rule, is usually achieved after the second time it is carried out.

Success Indicators and Instruments

We evaluated the success of this phase using one of the most cited models in professional development programmes [57]:

- Some teachers carry out the IBSTS by generating an inquiry dynamic in their classrooms (they call it "domain of practice and consequence"), and their performance serves, in addition, for other colleagues to take advantage of them. We did not expect every teacher at the school to carry out the IBSTS, but rather some of them to initiate that process. The initial number should be greater than the "tipping point" according to the critical mass theory (25%).
- Extent to which the teachers who carry out the IBSTS for the first time feel comfortable and secure in the face of change and express positive attitudes and a "desire for

more" ("personal domain"). To assess this aspect, we designed and conducted semi-structured interviews (Appendix B). The questions aimed at obtaining information on the following categories: (a) difficulties or obstacles felt in bringing the innovation into the classroom; (b) assessment of the effort required; and (c) emotions/attitudes felt and willingness to continue (i.e., what thoughts, sensations, or feelings have you had as a teacher?). Teachers' responses were audio-recorded and then transcribed. To analyse the interviews, we established three main categories: felt difficulties, assessment of the effort required, and emotions and desire to continue. Later, to organise and analyse the information from the interviews, we established subcategories based on words or phrases related to each of the categories (for example, for the category "felt difficulties" we established the subcategories "lack of. . .", among many others). Two of the authors reviewed all the questionnaires separately and categorised the responses (from the identification of the subcategories). Subsequently, they compared the results and discussed the discrepancies observed. In cases of discrepancy, the review of another expert (also an author of the article) was used. In this way, we were able to systematically examine the responses and find patterns.

- Finally, we assessed the satisfaction of families and principals with the change ("external domain"). To assess this aspect, we used questionnaires and reflections on notes in the field notebook.

For the families, we designed a questionnaire that was called "circular for families" (Appendix C), in which (in a generic way, without alluding to the project for changing science teaching) we asked them if they were aware of the innovations that were being carried out at their children's classes, how they learned about them, and if they noticed any unusual behaviour in their children related to the innovations. We asked them these questions two months after the innovation began at the school. In addition, to avoid conditioning the answers, the "questionnaire" had the school's logo at the top, and the principal was responsible for distributing it to children. To analyse the questionnaires, we carried out the same procedure as for the analysis of the questionnaire carried out after the training course (phase 1). The established categories were the following: the identification of the innovation in the children's class (yes or no), an explanation of how they learned about it, and the expression of some emotion. We calculated Cohen's Kappa coefficient, and we obtained an agreement rate greater than 95%.

On the other hand, to assess the satisfaction of the principal, we took into account the interactions (formal and informal meetings) that took place with the principal. Moreover, we paid attention—by means of notes in the field notebook and reflections of the research team—to identify factors that would facilitate or hinder the teaching change at the school.

2.1.3. Phase 3: Reflection Seminars on the Practice and Implementation of the Teaching Sequence for the Second Time by Teachers

From the beginning, both teams knew the first-time implementation of an innovation could always be improved. Two-hour seminars were held every week for three months after the first implementation, aimed at improving both the performance of everyone and the coordination of the sequence itinerary. Researchers' teams transcribed and edited the video records of the teaching sessions and selected episodes on the performance of teachers and students in some activities of the sequences. These episodes were discussed, and some behaviours of teachers and students were analysed. Sequences from different grades were first globally recalled and then analysed by all participating teachers. This favoured the coordination of teachers from different grades and the readjustment of some sequences to improve the coherence and progression of the teaching itinerary.

As discussed above, these seminars made it possible for the teachers to identify "misbehaviours", and their causes, and good performances. We hoped that this, together with the review of the focal questions, the plan to try to answer them, and the scientific content of the sequences, would produce a great improvement in their conceptual and methodological knowledge and their management of the class, which increased their self-

confidence [10] to put an IBSTS into practice for the second time. Some of the participants decided to join the innovation project in those seminars.

Success Indicators and Instruments

We evaluated this phase using these criteria:

- The implementation of changes in school organisation (timetables, prioritizing the teachers involved in teaching science, etc.) that facilitate innovation.
- Positive appraisal of the usefulness of the seminar sessions by the participants and the research team. We assessed this aspect from the annotations in the field notebook of the researcher leading the seminar.
- Teachers and students' behaviours. To assess whether the expected didactic change took place in their "way of acting" in the classroom and consequently also in the way students learn, we used an observation sheet adapted from the European Fibonacci project [63] (found in Appendix D) during several classes, whose items state priority aspects of inquiry teaching. Each item was rated with "Not Applicable/NO/YES" and, in the case of YES, with 1 (occasionally, sometimes), 2 (frequently), and 3 (it is part of their way of teaching). With this sheet, we also intended to detect weaknesses and strengths and try to improve them in future interventions.
- Self-evaluation of the committed teachers through a semi-structured interview (Appendix E). With this interview, we aimed at obtaining information on the following: (a) How they evaluated the way they used to teach and the way they did it with the IBSTS; (b) The difficulties/obstacles they felt during the process (from the intensive training course to the end of the second implementation of the innovation); (c) The persistence of the desire to continue/discontinue and reasons/motives. Given that our objective focuses on the sustainability of change, it is important to know whether they would carry it out again, and their reasons for that; (d) Emotions/attitudes they felt during the process (with this reflection exercise, we aimed at finding out whether there was a moment or turning point during this process in which the teacher began to feel more comfortable, secure, and confident in the face of change). This moment may be decisive and irreversible for him or her and may even mean that there is no turning back to conventional teaching (in the topic dealt with in the IBSTS developed during the process of change); (e) Factors that favoured the continuity of the project; (f) Assessment of the sustainability of the project at their school and its extension to others. The responses were audio recorded and then transcribed. The interviews were analysed following the same protocol as the rest of the interviews carried out during this plan.
- Student learning outcomes of teachers who implemented an IBSTS twice. We designed pre-test/post-test questionnaires and compared achievements between experimental and control groups using the chi-square statistic (with Yates' correction in cases where at least one expected frequency value of the contingency table was less than five). We considered that there were significant differences between the groups when $p < 0.05$ (for more details, see [59]).

2.1.4. Phase 4: Achievement of Lasting and Extensive Science Teaching Change

This phase should be considered the end of the process. In the first phase, intensive training was offered in methodological and conceptual knowledge, on specific contents, and linked to practice. Several problematised didactic sequences of increasing complexity on the same core idea of science were discussed by the participants, organised in small groups. In this intensive course, all the ideas—both those of the participants and those of the university professor, correct or incorrect—were considered as possible existing ideas of all the participants, treated with respect, and subjected to analysis and testing in a tentative and non-threatening climate. In this way, we hope that not only the methodological and conceptual knowledge of the content of teachers improved, but also coordination, feelings of group identity, and the strengthening of stronger and broader ties.

In the first implementation of an IBSTS (2nd phase), the university team helped committed volunteer teachers put the innovation into practice, from remembering the specific sequence to making "My Science Notebook" and practical materials for their students. On their part, they have allowed the video recording of their lessons. This would have strengthened social support and trust between both teams. Early insights into students' behaviour, attitudes, and learning also reduced feelings of personal risk in adopting the innovation. Finally, in the 3rd phase, the "reflection on practice" seminars should have improved teachers' mastery of the IBSTS, the credibility of innovation, solidarity, and deeper coordination. The second implementation of the same sequence and the measured results on student learning and attitudes, together with the evaluation of the families and the support of the principal, should have produced feelings of personal and professional success, increasing enthusiasm and group confidence in the change towards guided inquiry-based science teaching.

Therefore, we formulate the hypothesis that the structure and "rewards" [64] to achieve the consolidation of a critical mass or tipping point of 25% that makes the change spread to the entire organisation (the school)—the mathematical prediction of critical mass models for complex social contagions [44,46]—and becomes irreversible should be reached at the end of the 3rd phase.

In an operational way, if our hypothesis is fulfilled, in the course following the second implementation and the seminars of reflection on practice (4th phase), we should find that (a) The vast majority of teachers develop an IBSTS (some for the third time) with a duration of at least 20% of the total hours devoted to science in each year (56 h); (b) The sequence itinerary has been adopted throughout the primary stage so that students could learn progressively and coherently about the core idea addressed; (c) The school staff (teachers and principal) request training to be able to teach a new core idea of science by guided inquiry. Lasting and, we believe, irreversible change would have been achieved.

Now, we present the school (and the group of committed teachers) where we implemented the designed plan. After that, we will present the most important results obtained after more than four years of work (longitudinal study). These results also identify which interventions facilitate (or hinder) the desired professional change.

2.2. Participants

The project was carried out in a Spanish school; it was a convenience sample near the university. Initial contact was made through acquaintance between some members of the school and university teams. This school is private, but free for parents because it receives public funds, and the socioeconomic and cultural level of the families is medium. About 10% of the students are of foreign origin and have difficulties speaking Spanish. The school had twelve generalist primary teachers (teaching science, among other subjects) and three specialists (teaching music, English, and sports), who had between four and twenty years of experience. The principal, as considered by teachers, exercised strong leadership, and she was willing to propose and manage initiatives to improve teaching.

3. Results

Results are presented following the phases described above in order to determine the failure (or success) of each and try to identify causes for that to happen.

3.1. Phase 1. From Plan to Practice: The Training Course

In this phase, we held formal meetings with the principal and later with all teachers to present our project. We show the itinerary of sequences elaborated (from 1st to 6th grade) on "How are all things made inside? How are they similar, how are they different?" within the Matter and Energy content of the Spanish Official Curriculum for Primary Education [8] (see Appendix F). In addition, we explained the phases of our didactic change plan and presented some evidence of specific results on children's learning obtained in sequences previously tested in other schools.

After several meetings, the principal was very interested in incorporating innovation at school and improving the shortcomings they had (reading the textbook, teaching loose items, lack of training and knowledge on certain science topics). Given the good reception, we established commitments on both sides: teachers from the school would attend a free training course on the sequence itinerary previously presented, and later, those interested, on a voluntary basis, would carry out the sequences with their students; from our part, in addition to the course, we would offer the necessary help (inside and outside the classroom) so that the innovation could be put into practice. Besides, the school agreed to allow the university team to obtain data to assess students learning and video record the lessons. To this end, parents were informed about what was being performed and their written consent was sought; an agreement was signed with the university and reviewed by the legal services, stating all the terms of the agreement.

After the school accepted to be involved in the project (success indicator), we carried out the offered training course. The course took place during non-teaching hours and lasted for 40 h in two weeks. Thirteen in-service teachers attended (twelve generalist teachers and one specialist sports teacher).

3.1.1. Evaluation of the Training Course

Table 1 shows the results obtained from the first part of the training course assessment questionnaire.

Table 1. Anonymous assessment of the professional development course. Items are scored by in-service teachers according to a Likert scale (1 = very negative; 5 = very positive). In this table, "teacher" refers to the member of the research team who conducted the course.

Assess the Following Aspects of the Course in Which You Have Just Participated	**School (n = 13)**	
	$\overline{x}$	*Sd*
1. Interest of the contents of the course	4.5	1.2
2. Coherence between proposed objectives and methodology	4.9	0.3
3. Classroom climate	4.7	0.8
4. Time-content relationship	4.5	0.5
5. Mastery of content by teacher	5	0
6. Clarity in teacher explanations	5	0
7. Teacher methodology for developing sequences	4.8	0.6
8. Teacher ability to increase my interest in inquiry-based science teaching	4.8	0.6
9. Learning scientific contents (to me)	4.4	1
10. Learning how to teach using and inquiry-based science teaching approach	4.3	0.8
11. Explanation of the specific objectives of the sequences	4.8	0.4
12. Achievement of the objectives of the sequences	4.7	0.6
13. Sequences of activities (structure, interest…)	4.7	0.6
14. Orientation (important question to be solved)	4.5	0.7
15. Adequacy of sequences and materials included	4.8	0.4
16. Applicability of sequences	3.8	0.8
17. Interest in introducing inquiry-based sequences in the classroom	4.5	0.7
18. Interest in putting into practice the sequences	4.4	0.7
19. Willingness to continue in the project	4.4	0.7
20. Degree of usefulness of the sessions	4.4	0.7
21. The way how the course has been developed	4.7	0.5
22. Overall assessment of the course	4.8	0.4

As observed in Table 1, teachers at this school rated the course quite positively. They considered that the objectives set at the beginning had been fulfilled and that the course had coherence between its aim and the methodology used to develop it. Since our goal was for teachers to bring innovation into their classrooms, their assessment of the IBSTS and its applicability in the classroom was relevant (items 11 to 16). The average value of both items was higher than 3.8 points out of 5, so it was clearly positive. However,

teachers had doubts about the applicability of the sequences in the classroom (item 16). Teachers affirmed that they rated this item lower because they were concerned about the lack of space and materials (for example, they did not have measuring instruments—i.e., scales or graduated cylinders—and classrooms were quite small according to the number of children inside). Finally, as seen in items 9 and 10, the course was useful for teachers to improve their knowledge on the topic and, at the same time, on how to teach science using an inquiry approach. Their interest in introducing some of the sequences developed in the course in their classes and continuing in the project was high (items 17 to 20). In informal conversations at the end of the course, many teachers mentioned that this training course was essential to being able to take the sequences to the classroom, which was reflected in their overall evaluation of the course.

3.1.2. First Difficulties Felt in Implementing Innovation

At the end of this intensive course, teachers were more aware of what it entailed to carry out an IBSTS in the classroom, so we asked them to reflect on the difficulties or needs to bring this innovation into the classroom. These results are shown in Table 2.

Table 2. Difficulties cited by the 13 participating teachers to implement problematised teaching sequences (by themselves and by other non-participating teachers) at the end of the training course (f: number of teachers expressing a difficulty).

What Do You Think Are the Main Difficulties in Bringing the Guided IBSTS to Your Classroom?	**Referred to Themselves**		**Referred to Non-Participant Teachers**	
	f	%	*f*	%
Lack of personal involvement (attitude, willingness to work)	8	61	10	77
Lack of scientific knowledge	1	8	6	46
Influence of the physical environment	8	61	2	15
Lack of time	3	21	0	0
Lack of material resources	8	61	0	0
Lack of training	0	0	9	69

As can be seen, teachers did not cite the same difficulties when referring to other non-participant teachers. The main factor or difficulty was the attitudinal involvement of the teacher—the fact of dedicating personal time and effort outside the working hours to preparing the sequences for action. This was an important obstacle, as it was mentioned by 77% of the teachers when referring to "other colleagues" and 61% when referring to themselves; however, it is always necessary to do personal work to move innovation from a training course to the classroom. The research team can help to create what Hutner and Markman call "mediating representations" [65], that is, they can work to improve all those limitations and aspects that influence the achievement of a goal, such as by taking some of the worked sequences to the classroom. But, if teachers do not invest time in preparing what they are going to teach (even if they think it would be the best way to do it), there will be no "activation of the goal" (the "action" will not be carried out), and therefore, the change will never take place. The rest of the difficulties were related to the findings of Harrison et al. [66] and are well known and include a lack of scientific knowledge and circumstantial obstacles (influence of the environment, lack of time, and human and material resources). When they referred to other colleagues, in addition to the above-mentioned personal involvement, both the lack of scientific knowledge and training appeared as very prominent difficulties; the difference in these two aspects could also be regarded as an indicator of the success of the training course to overcome some shortcomings felt by teachers in the first phase of the plan. But, also, these results indicated

that if we want teachers to carry out an IBSTS in their classrooms, it is not enough just to attend a course and overcome some of the well-known limitations; they need to want, that is, their professional goal be to improve their teaching, using the time and effort that it requires [65].

After this analysis, we can affirm that the success indicators of the first part of the designed plan were attained: obtaining the necessary consensus to accept the university team to work together to improve science teaching; positive evaluation of the training course received; and obtaining reliable information on the obstacles felt by teachers to implement an IBSTS.

3.2. Phase 2. From the Training Course to the Classroom: First Implementation

Out of the 13 teachers who attended the course, five volunteered to put into practice some of the sequences developed and to be videorecorded (two men that we will call Fran and Juan, and three women that will be called Isabel, Ana, and Marga; these names do not correspond to their real names). The critical mass for the school was three, so five was considered a good number to start with. Although the training course was recent, before the first Implementation, two sessions of two hours for each sequence were held with the teachers to review the sequence, solve doubts, and prepare some materials for the children to work with. During these sessions, there was an atmosphere of collaboration; however, recording is an invasive and uncomfortable intervention, so the teachers were a bit worried about this. Five teachers developed some of the planned sequences in a total of six groups, from 1st to 6th grade. During this process, the principal facilitated timetable changes, and hence, sessions of 1.5 or 2 h could be held two or three times a week until the sequence was completed (success indicator). The average duration was 13.5 h/sequence. To obtain data on children's learning, pupils up to 4th grade were interviewed (the youngest ones) or answered a written questionnaire before and after the teaching. For children in the 5th and 6th grade groups, a pre-test/post-test questionnaire was administered, and responses were compared to those of control groups from another school with a higher socio-economic context. From these results, teachers were aware of improvements in learning in the experimental groups. These first results, as previously explained in the plan, were used only for internal analysis and for improvement in a second implementation.

3.2.1. Assessment of Teachers Involved

The five teachers involved were interviewed using a structured questionnaire to detect their reflections and emotions after the first and second implementations (in the next phase) to see the evolution. We show below some representative extracts of the aspects they mentioned after the first implementation:

- On the difficulties felt

Isabel, a 3rd and 4th grade teacher: "The impediment or obstacle was also the classroom, because I thought that to do this work it was necessary to have more space outside the classroom (she referred to the difficulties mentioned during the training course). Now, after having done it, I have realised that maybe this is not so important and, if everything is well organised, this is not as difficult as I thought".

Fran, a 4th, 5th and 6th grade teacher: "Let's see, it is a type of methodology that I really liked, but it requires meticulous preparation before doing the sessions, more than what we are used to. It is true that once you get into the working dynamics and see the whole sequence and if you have done it several times it will not be so hard, but at the beginning it has been a little bit more difficult than what we are used to working with".

At the training course, teachers agreed that one of the main difficulties was the lack of scientific knowledge and training (when referring to other non-participating teachers), in addition to other factors such as the influence of the physical environment, time, or lack of material and human resources. However, at this phase, all five teachers interviewed (responding individually and separately) agreed on the difficulties expressed. None of them cited a lack of training, so the training course improved their knowledge on the content

related to the storyline "How are all things made inside? How are they similar, how are they different?". On the other hand, the difficulties expressed after the first implementation were very different from those they felt after the course, focusing now on methodological aspects of teaching (how to act) and classroom management.

After the first implementation of the innovation, the most important obstacle was "wanting to do it", after "overcoming the fear of doing something new for the first time". Thus, when they are confronted with change for the first time, circumstantial obstacles disappear, and personal involvement becomes the main "hindering" factor.

- On the assessment of the effort required, emotions/attitudes felt, and the desire to continue

Ana, a 1st and 2nd grade teacher: "What I liked the most was seeing the enthusiasm of the children [. . .] and seeing how they have learnt. Although it is a small thing now, it does give you an idea of what it could be like. I see that there is another way of doing things and that we can do things better. I can tell you that clearly, children learn; it is not that they do not learn now, but we can do it in another way, and it might be more meaningful for them".

Isabel, a 3rd and 4th grade teacher: "The children have learnt, they have understood it much better than if you give them the classic lesson on the subject. They are all excited, and they remember everything and every detail. And the parents are very happy [. . .]. When I had taught the subjects in natural sciences, especially these subjects that are so complex to explain to small children, I found it a bit difficult, I said, "How do I teach them? And I always teach it quickly [. . .]. And when I have now done it this way, it has encouraged me to do it every year so that they understand it and retain the important ideas. I really believe that they have understood everything perfectly".

We have presented two excerpts, but the five teachers interviewed gave very similar answers. Teachers felt "rewarded" after implementing the innovation. They felt that their students had learned more and better. In addition, they felt the support of both the families and the principal and their own satisfaction with what they were doing ("I found it uncomfortable", said Isabel, referring to the usual teaching). Moreover, they all expressed phrases of enthusiasm and eagerness to put the innovation into practice again: "I am looking forward to repeating it next year [. . .]. I am really looking forward to it. And I would love to do more of my course, because I learnt with the course, but when you really learn, it is when you put it into practice with the children"; "It has changed my concept of teaching, so much so that I would like to work more in this way, I have seen that we can make children to think". Overall, they all expressed that they would repeat it the following year.

3.2.2. Assessment of the Principal Team

In our plan for didactic change, the final decision to implement an IBSTS depends on teachers, although the principal has a key role in driving and facilitating the change [67,68]. If the school leader promotes situations that foster professional interaction and collaborative support for innovation, teachers are likely to be motivated to continue [69,70]. Although we do not show quantitative data on this, we present descriptions of our team's field notebook entries and reflections: the actions of this school's leadership match those of an effective, transformational leader. One of her key decisions included providing time (2 h/week) during the school day for committed teachers to attend meetings and seminars to prepare for the intervention, together with the university team and other committed colleagues [71,72]. In addition, the principal promised to support them by allocating resources to purchase the necessary materials that would allow them to develop more open and active science teaching (in the meantime, they borrowed the necessary materials from our team). From this perspective, teachers felt rewarded and strengthened to continue.

On the other hand, the principal/teacher teams were in almost daily contact with our research team. The principal was continuously interested in the progress of the project and was also very positive about the innovation carried out at the school. Teachers expressed their interest in continuing the innovation project, and they expressed the idea that all the science content in the curriculum should be developed using an inquiry-based approach. Thus, it seemed that one of the success criteria of this phase, the assessment and positive

impact of the project in the "external domain", was being achieved. To be able to affirm it reliably, we only needed to know how the families valued the project (see next section).

3.2.3. Assessment of Families

We evaluated the satisfaction of families with the changes [73] from the questionnaire that we called the "circular for families". The principal handed out a total of 73 questionnaires (to the groups of pupils who had been taught by inquiry), and 48 were received back. Results obtained for the three questions set in the questionnaire are presented below (Table 3).

Table 3. Results on families' knowledge and satisfaction with the change in science education.

Generic Open-Ended Questionnaire (see Appendix C) (without any reference to science education)		
Questionnaires sent: 73 **Questionnaires answered and returned: 48 (return rate 65.7%)**		
	n = 48	%
1. They identify "innovation" in their child's class as a change in science teaching.	47	97.9
2. They have known innovation:		
- By meeting at the beginning of the school year with the principal	24	50
- From what their children told them	21	44
- No answer	3	6
3. Expressed positive changes (joy; communication of what has been done; increased learning) in their children's behaviour at home, related to the change in science teaching.	39	81

The results of this questionnaire were clearly satisfactory. Out of the 48 questionnaires analysed, 47 identified "innovations" with the change in science teaching, and only one of them referred to other changes that had taken place at the school (mentioning that "hangers were installed at classrooms"). Moreover, in the first question, some family members described in detail what the science project in primary school consisted of, and they even wrote down some of the most important ideas of the sequence developed in their children's classes:

Family member of a 4th grader: "Experiencing science in a practical way, specifically the topic of matter and energy. My son tells me that they have seen if air weighs, if air can be seen…".

Family member of a 1st grader: "As far as we know it is a project for the subject of Natural Science, so that the children learn not only with the book, but also by "investigating in groups". They have done some work using different textiles and materials and asking the children about it".

These responses show that the project had an impact on the pupils because they reported on the activities carried out at home. In that sense, 44% of the family members stated that they were aware of this project through their children (second question), 50% of the families were aware of the project through the initial meeting held at the beginning of the school year, and the remaining 6% did not answer this question or referred to another type of innovation.

The most striking results appear in the last question, which shows that 81% of the families stated that children showed more excitement, involvement, interest, curiosity, and/or better learning during the implementation of the innovation. Here are some extracts from the responses of the family members:

Family member of a 3rd grader: "I have seen my daughter very motivated and excited about the project. In addition, I think she has learnt more than with traditional lessons".

Family member of a 3rd grader: "Yes, she was happy every day telling us what she had seen and experienced in class. She was especially sad to see those classes end".

Family of a 3rd grader: "Not different, but he has shown a lot of interest and he has been telling us everywhere air can be. He has conducted some of the experiments at home, and it was really great"!

They not only expressed the positive emotions felt by their children, but also valued them satisfactorily ("the truth is that it was great"; "he learned more", among other comments). On the other hand, 17% of the family members answered that they had not noticed any behaviour different from their usual behaviour, and 2% responded by referring to another type of innovation. In short, based on these results and on the constant comments of gratitude and satisfaction that the family members transmitted to us in person, we can affirm that the families valued the implementation of the innovation in the classroom very positively.

Therefore, with all the results presented here, we can affirm that all the indicators of success of the second phase of our programme were met: we achieved the commitment of five teachers, who said they wanted to do more. Their practice was reinforced and "rewarded" by personal satisfaction with their own work and by the school's principal's and families support and satisfaction. The success of this phase allowed us to move on to the third, whose results are as follows.

3.3. Phase 3. Reflection Seminars on the Practice and Implementation of the Teaching Sequence for the Second Time by Teachers

3.3.1. Usefulness of Practice Review and Reflection Seminars

The first development of the sequences was followed by seminars of two hours per week for three and a half months (28 h). All the teachers who wanted to participate were invited, in addition to the five committed (those who developed the IBSTS), and they were informed of the convenience of knowing what had been performed with their students that year and what could be performed in the following year. A total of 10 teachers regularly participated in the seminars. Seminars began by recalling together the storyline that gave coherence to the teaching itinerary and the specific IBSTS within it. Videoclips selected for showing some important episodes (both well-developed aspects and those to be improved) of the sequence in action were then presented, and teachers were asked to express what they thought about the activity of both students and teacher and how it could be improved, if necessary. Those were true behavioural (co)construction sessions [10,40]. The initial reluctance to be criticised quickly disappeared due to the climate of learning and improvement between them. A first result of these seminars was the identification by the teachers themselves of deficiencies ("misbehaviours") that were repeated—which facilitates training, just as knowing misconceptions does—in all the sequences in the first implementation:

- Not allowing groups of students the necessary time to think about a possible answer or logical plan. Not encouraging different answers (they looked only at the answer they expected: the first one that was correct). Ignoring some of the students' ideas because they had not planned what to do with them.
- Anticipate the content of activities instead of waiting for the right moment. Their way of teaching was very ingrained; it was difficult for them not to say what they knew or not immediately give the answer to a doubt or question. They found it difficult to wait and to invite students to be part of the inquiry.
- Lack of appropriate mastery of the initial question that guides the sequence's argument thread. Not frequently reminding students of that question and the plan being followed to try to answer it. That is, they used the problematised sequences as a series of unconnected activities or tasks that had to be performed, ignoring the relationship and connection between them.
- They still had some conceptual or terminological errors on the specific topic.
- Lack of preparation. Teachers recognised that, in most cases, this was the cause of the previous situations.

After the follow-up and improvement seminars, our perception was that there had been a qualitative change in the preparation of teachers, which had to be confirmed with a way of teaching that is consistent with inquiry teaching and with the results of their students. One of the committed teachers (whom we call Juan, teacher of 1st and 2nd grade) did not continue for personal reasons, but a teacher who had only participated in the follow-up seminars joined the group of committed teachers.

3.3.2. Analysis of Classroom Dynamics

Table 4 presents the analysed items (which are fundamental aspects of inquiry teaching) and the assessment of the achievement of each item by the four teachers involved. The observer was one of the members of the university research team. Around four hours (non-contiguous) of each teacher's intervention video clips were analysed. Each item was rated with "YES/NO/Not applicable (NA)" and, in the case of YES, with 1 (the item is carried out occasionally), 2 (the item is carried out frequently), and 3 (it is part of their way of teaching).

Table 4. Results of the classroom dynamics generated during the second implementation of the innovation by the four teachers involved.

Items Section A: Teacher-Student Interactions	**Ana (1st Grade)**		**Marga (1st Grade)**		**Isabel (3rd Grade)**		**Fran (5th Grade)**	
	Y	N	Y	N	Y	N	Y	N
1a Teacher asks questions aimed at students to express their ideas	3		3		3		3	
1b Teacher helps learners to formulate their ideas	3		3		3		3	
1c Teacher gives students positive reinforcement on how to check their ideas	3		2		3		3	
2a Teacher encourages predictions	3		3		3		3	
2b Teacher involves students in the investigation	3		1		3		3	
2c Teacher encourages checking their predictions	3		3		3		3	
2d Teacher encourages and assists in collecting data	3		3		3		3	
3a Teacher asks students to present their findings	3			X	3		3	
3b Teacher asks students to match their conclusions to their results	2			X	3		3	
3c Teacher asks students to compare their conclusions with their predictions	3		1		3		3	
3d Teacher asks learners to try to give reasons or explanations for what they have found	3		2		3		3	
Items Section B: Student Activities	Ana		Marga		Isabel		Fran	
	Y	N	Y	N	Y	N	Y	N
4a Students work on questions that they feel are their own	3		3					
4b Students make predictions	3		3		3		3	
4c Students participate in the research plan	3			X	3		3	
4d Data obtained allow students to test their predictions	3		3		3		3	
4e Students consider their results in relation to their questions	3		2		3		3	
5a Students collaborate when they work in groups	3		3		3		3	
5b Students engage in discussions about their investigations	NA		NA		3		3	
5c Students present their work to each other	3		3		3		3	
5d Students listen to others when they communicate results	2		2		3		3	
5e Students take notes on what they have done	3		3		3		3	

The four teachers who implemented the innovation for the second time moved from reading and paraphrasing from the textbook to making inquiry-based teaching their way of working. This, for example, included asking questions (items 1a, 1b), encouraging pupils to communicate their ideas and predictions (2a), carrying out a 'simple' plan (2c) which pupils test, draw conclusions (3a, 3b, 3c), and record them (5e), and working in teams (5a) guiding the sharing (5d). In addition, it was remarkable that all teachers transformed the

physical arrangement of tables, materials, and students. They prepared in advance the materials to be used in the session and arranged them perfectly to give them (and take them away) to the groups of pupils at the right time, which facilitated order in the classroom. However, although the changes were very evident, there were also weaknesses that needed to be improved, which were discussed with the research group. For example, as can be seen in Table 4, Marga was still very entrenched in her usual practice, especially in research planning and communication of results. In most of the observed sessions, she tended to communicate the plan to the students and/or verbalise the conclusions and recaps instead of involving children (along with her) in these tasks. However, working with the research group and her attitude and willingness to work helped overcome these deficiencies. Hence, we can affirm that changes to the usual way of teaching were very positive and profound in all cases after the second implementation.

3.3.3. Assessment of Student Outcomes

To measure student outcomes, learning indicators were developed for each sequence according to their objectives as well as the grade for which they were developed [59]. Questionnaires were designed and pilot-tested to see if they were appropriate for the age and reading level of students. After that, they were modified accordingly to be used as a pre-test and post-test. They were administered one week before (pre-test) and one week after (post-test) teaching. Two members of the research team separately rated the answers as correct/incorrect and, within this division, into different categories representing the most common answers [59]. For open questions, Cohen's Kappa coefficient was calculated, and, three months later, the intra-judge Kappa index, with an agreement rate greater than 95%. The number of meaningful ideas expressed by students in their answers to questions such as "In class, we have discussed…; How would you explain to a friend who has not been in class the most important ideas about…" were also measured to assess the appropriation and linguistic progress of the learning achieved. Differences in children's knowledge attainment between experimental and control groups were significant (with χ^2; $p < 0.05$) in all sequences taught by teachers for the second time and in one taught for the first time (about density in 5th and 6th grades).

3.3.4. Assessment of Teachers Involved

Structured interviews with teachers about their feelings on the second implementation were recorded one week after the end of each teacher's intervention and transcribed for comparison with the first ones. Below, we present a table of the most important ideas mentioned by three or more of the interviewed teachers in this phase. These results, summarised in Table 5, are very useful for scaling up and eventually extending the change to other schools.

This phase allowed us, on the one hand, to identify "misbehaviours" that were repeated in all the sequences in the first implementation—whose knowledge will facilitate training and extension to other sequences and schools—and, on the other hand, to identify aspects/factors that most of the teachers involved mentioned as important aspects that influence the consolidation of the change. The concerns of teachers after the first implementation were very different from those expressed at the end of the training course (results of Table 2 compared to Table 5), with the latter focusing on methodological aspects of teaching (how to act) and classroom management. They all agreed on the great importance of the seminars to review the sequences and the analysis of the video clips of the lessons to overcome them. After the second implementation, the methodological obstacles disappeared because they claimed to have gained confidence in the way of planning the teaching (by guided inquiry) and, at this phase, the main "difficulty" is the investment of time required to prepare the intervention, although they expressed that this will become less and less. They recognised that the principal had provided resources and organisational changes to support the change (another indicator of success for this phase).

Table 5. Aspects highlighted by three or more teachers interviewed after the second implementation.

Important Ideas	No. of People Who Mentioned Them (Out of Four)	Representative Excerpts
First implementation: teachers must overcome the fear of doing it for the first time	3	"The biggest change was last year when I did it for the first time (. . .) And you can see that it has changed completely; it has been a 180-degree turn. This year I have not noticed that change because I already knew what I expected, and I knew what it was going to be like" (Isabel). "It's also true that the first time, there is always the insecurity of, 'Will I do it right, are they looking at me, what is going to happen?" (Fran).
On how they taught before and how they have performed it now (huge change: methodology; teacher-pupil or pupil-pupil interaction; classroom layout of the pupils)	4	"Well, the change in methodology has been huge. Starting from the organisation of the classroom, as children were not in a team before and now, they are in a team. Moreover, since we started with this last year, they have been working as a team with me all year round. And also, in terms of learning, it is much more significant. (. . .) Otherwise, learning is more mechanical and repetitive. Overall, it is very positive" (Ana).
The emotional evolution felt during the process: from insecurity and tension to confidence and calmness. The first implementation: "it's hard"	4	"The first time I taught it, I did feel enthusiasm, interest, curiosity, fun and motivation. I was not afraid, I was a bit insecure, maybe because it was the first time and I had to focus and adapt to how you teach it. Now, at this moment, it would be enthusiasm, calmness. (. . .) Of course it is difficult the first time because that is what it is, you have to start teaching it, you do not know how they are going to react, you have never done it before, and so, even if you are very prepared, you do not know. The first time it is hard, but I think that from the second time onwards, you also feel more confident, and you become more comfortable" (Isabel). "(the first time) I was very tense, nervous. It was fun and I was motivated, but very overwhelmed, I had someone recording me and listening to me. Of course, I was curious to know what was going to happen (. . .) but I was anxious and insecure, I had everything". Now (second implementation), I am calmer, and I think next year, much better (Marga).
Internal factors influencing continuity: students' learning and attitudes and professional satisfaction	4	"The most useful thing is the motivation of the pupils, the videos of the children. That was what had the biggest impact on me, then there was the parents reaction and my own. But the first thing has been how they have learnt, how they have owned all the concepts you have taught them, how they verbalise them, how they write them down in the scientific notebook, how they know how to do it, how they did the experiments and how they recorded them. I could see how they said: tomorrow is science (. . .)" (Isabel). "I loved it. They learn so much, I loved it" (Fran).
External factors influencing the decision to continue: principal support and training	4	"The principal has been everything. She has bet for the change, and we have to continue in this line, I am happy" (Ana). "The principal is totally involved; she likes it a lot. (. . .) The principal 100% (. . .). If I had to face all the insecurities on my own from the beginning, as I did not know what was going to happen, as I had a bit of insecurity, it would have cost me more. But having the support and having done it myself, I am now confident (referring to the support of the university team)" (Isabel).

Thus, based on the results presented, we can affirm that we achieved the success indicators of the third phase of our plan: after the second implementation, a critical mass of teachers teaching science by guided inquiry was reached and consolidated.

3.4. Phase 4. Achievement of Lasting and Extensive Science Teaching Change

After the positive results of the third phase of our plan, teachers and the principal asked us to extend the training and to continue with another itinerary of IBSTS (i.e., to start with another core idea of science) because "they wanted to teach all the science contents in this way". Thus, we conducted a new training course on a new IBSTS itinerary about another structuring question for the primary education stage ("How is the Sun path? Is it always the same? Does it change? Does it repeat itself?", "Can we use it for organise time and space?" (see Appendix G). Eighteen teachers attended, nine from the first school and nine from a new school that had known about the project in an oral presentation at a professional seminar. Some, or more of the needed critical mass, of the new teachers attending committed themselves to incorporating the new sequences into their academic planning. Unfortunately, in March 2020, the COVID-19 pandemic did break the planned development of the project, when we were working at the new school. Normality, although with some restrictions on how to manage the distribution of students' space in the classroom, came back by the 2021–2022 scholar course.

To assess this fourth and final phase of our plan, we must see it as a consequence from our hypothesis: if a critical mass of teachers who teach science through inquiry is generated in one of the phases of the plan, who feel rewarded for their efforts and peer coordination is encouraged, the change will eventually spread to a large majority of teachers to teach science using our methodological approach. Taking into account that didactic change is a complex behavioural change [45], we adopted the conservative criterion of considering that the critical mass is reached when one third of the teachers teach science by inquiry for two or more school years, using 20% of the hours of the subject Nature Science. This criterion was reached at the end of the third phase: four teachers had put into practice inquiry sequences within the planned storyline, using an average of 13.5 h of the 56 h allocated to science (a percentage higher than 20%); their pupils had attained very good learning results; the principal and families supported them; their peers had participated in the seminars; and they had personal satisfaction. Once this critical mass has been achieved, the change should eventually spread to a large majority of science teachers. This extension should logically be reflected in a progressive increase in the number of hours and groups of pupils in the school who receive inquiry teaching. Thus, to evaluate this fourth phase, we present Table 6, which shows and quantifies the evolution of inquiry-based teaching in the different phases of our plan.

As can be observed in Table 6, at the different phases, the number of groups and the time invested in teaching science by inquiry increased. In the second phase, the number of groups was only six; this seems logical because, at this phase, fears are at bay and they are confronted with change for the first time. In the third phase, the number of groups increased thanks to organisational changes made by the principal because they assigned the teachers involved to be science teachers. Thus, out of the seven teachers who taught science, five of them implemented a problematised sequence in one or more groups. The number of groups increased from six to eight, and thus, the total number of hours devoted to teaching science by inquiry also increased. However, at these phases (second and third), there is still no progression or continuity throughout the primary school on the core idea of science addressed in the process of change (four groups out of 12, followed a regular teaching on "properties and common structure to all materials").

At phase 4 (academic year 2019–2020), changes were very important: it was planned that all teachers who taught science would carry out some inquiry-based sequence in classrooms (thanks to the changes promoted by the principal), and therefore, the time spent would increase enormously, up to 45.5% (after incorporating a new sequence's itinerary). Although these data were expected for the whole school year, due to COVID-19, teachers

could only develop the IBSTS until March. After the confinement due to the pandemic and the promotion of health restrictions, in the following school year (2021–2022), the school returned to "normality", and resumed the project. As can be seen in Table 6, all groups of pupils received inquiry-based teaching on "properties and common structure of materials" (as the teaching of these IBSTS was well established). However, they did not carry out the teaching of "diurnal astronomy" sequences because, unfortunately, the pandemic prevented teachers from owning the sequences. Therefore, based on all the data presented in this paper, we can affirm that our plan for didactic change in this school has been both possible and irreversible. We are confident to affirm that our hypothesis on the theory of critical mass has been confirmed, and thus, the objectives of this phase were successfully achieved.

Table 6. Evolution of inquiry-based teaching in the different phases of the plan (** planned for that year, but could not be accomplished).

	Number of Teachers Teaching Science at the School	Teachers Who Carried Out the 1st Implementation	Teachers Participating in Seminars (28 h)	Teachers Who Carry Out the 2nd (or more) Implementation	No. of Innovation Groups (out of 12)	Average Number of Hours and % of Science by Inquiry in the Innovation Groups (out of 56 h)	Participants in the New Training Course on a Different Storyline of Sequences	Student Results Pre/Post Questionnaire Significant Differences ($p < 0.05$)?
2nd Phase 2017–2018	9	5			6	13.5 h 24%		YES
3rd Phase 2018–2019	7	1	10	4	8	13.5 h 24%	Continuity of training requested; intensive initial training was provided (2 schools, 18 participants, in July 2019)	YES
4th Phase 2019–2020 (Incorporation of new sequence itinerary) (** planned, but COVID-19)	8	2		6	12 100%	25.5 h 45.5% (**)		
4th Phase (post-COVID) 2021–2022	6			6	12 100%	13.5 h 24 %		YES

4. Discussion

According to the data obtained, the plan designed to achieve the didactic change from traditional science teaching to guided inquiry-based teaching was successful in the school where it was developed. The phases into which we divided the plan (and the results obtained from them) had many features that coincided with those identified in other effective professional development programmes [37,52,54].

In the first phase of the plan and after receiving the initial training course, teachers expressed the same difficulties in implementing the innovation as those that had already been widely documented in the existing scientific literature (such as a lack of training and knowledge) [21–23,25]. However, the analysis of the evolution of the concerns felt during the process of didactic change is something genuine about this research. These findings were very important because they allowed us to identify "hindering patterns" that appear during the change process, so they could be very useful for designing future professional development programs in order to overcome them and achieve the desired didactic change.

Our plan also coincides with considering changes in the different dimensions and processes involved in the professional growth of teachers. Therefore, according to one of the most cited models of professional growth, the "interconnected model" [57], the evaluation

of the second phase (and the subsequent ones) is based on a continuous cycle of learning and development, where we included the influence of all members of the educational community (teachers, principal, students, and families).

On the other hand, we agree with the findings found by Roth et al. [52], where they highlight the importance of using video analysis as an effective tool for the professional development of teachers and student learning in science. Roth et al. [52] also conducted a longitudinal study involving 22 high-school science teachers in a professional training course where they were given repeated opportunities to analyse and discuss videos of their own science lessons [10,55].

In addition, we agree with the conclusions obtained by Van Driel et al. [41] in their review of the scientific literature on effective characteristics (and deficiencies) in the design of professional development programs in science; we agree that fluid and sustained collaboration between the university team and the teaching team of schools is essential for the change. Collaboration generates security and trust and helps to overcome the stress of the first implementation, which is a key moment to start the change.

Our plan also had differences and singularities with respect to other studies. One of the differences with other programmes was the incorporation of the critical mass theory, trying, from the beginning, to create a group of teachers willing to teach science through guided inquiry at different levels, with strong personal and professional relationships (strong ties), and favouring a climate of reinforcement towards this group (from the principal and families) [44–46]. And, above all, trying to create satisfaction with their own work, justified by the students' learning and attitudes [41]. Another difference was the operationalisation of indicators to evaluate the achievement of the objectives at every stage, which has not been previously considered in other studies. Another difference is that the teaching sequences represent a learning itinerary throughout primary school on one of the subjects most "rejected" by primary school teachers: Matter and Energy [18]. Students' learning about the existence of different and common properties in "all things" from 1st to 6th grade (with concepts such as mass, density, and electric charge in the later grades), assessed by pre- and post-tests, was much better when compared to control groups, and these results will be published elsewhere. Thus, in our research, we have also addressed the gap commonly found in most studies on professional development programs in science by looking at the impact of implementation on student learning outcomes [41]. Finally, something unique about this research was also developing six sequences for different levels in an intensive course, which allowed five teachers to work with IBSTS at three different levels simultaneously since the first implementation. This situation encouraged cooperation and prevented teachers at higher levels from being unaware of what was being performed at the initial levels (and vice versa), and it made it easier for everyone to feel that they were all part of the same project.

Once the findings of this work have been discussed, we will proceed to present the conclusions obtained from them.

5. Conclusions

The design of a plan divided into phases and the operational definition of success indicators in each of them has facilitated systematic research on how to achieve "real" didactic change and, in the case of finding obstacles, identify the causes. The designed plan has made it possible to achieve the desired, sustainable, and irreversible didactic change in a school.

As this is a case study, the conclusions may be limited. With this in mind, we can state the following:

(1) The critical mass theory of complex social change has been useful in strategically designing a plan for achieving sustainable didactic change in science education.
(2) A key aspect for the success of the plan after the intensive course is to obtain a critical mass of teachers committed to the first implementation by allowing their classes to be recorded. We recommend that the number be close to 33% of teachers who teach

science. If the number is less than 25%, the university team should seriously assess the ratio between the effort invested and the probability of success.

(3) The consolidation of the critical mass is achieved after participating in the evaluation/reflection seminars on the first implementation and the subsequent improvement in the second implementation. The tipping point is reached after the second implementation.

(4) Teachers' misbehaviours in the first implementation are common to all teachers and sequences at the different levels. This is useful to anticipate them (as it is performed with the spontaneous ideas or misconceptions of the pupils) in order to improve.

(5) The willingness of the principal to support and make the necessary changes to facilitate inquiry teaching is very important. Similarly, there is a need to have families express their satisfaction—which is often driven by their children's enthusiasm—and to share this with the teachers who are implementing the change.

(6) The amount of work invested by the research team is very high. Therefore, if we want to extend this change to more schools, we need to seriously consider the sustainability of our effort. This can be achieved by changing the initial training curricula for primary school teachers (which is unlikely in Spain) and/or by testing whether some of the necessary activities for the proper development of the scheme can be carried out on a semi-presential basis with the concerned schools.

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Appendix A

Evaluation Questionnaire For The Primary Education Teachers

Training Course

We are very interested in knowing your opinion about the training course you just received. However, keep in mind that some psychologists say that after an intense training course, the assistants almost always value it well because they have spent their time and/or they have empathised with the professors. Therefore, they usually do not admit that they have wasted their time or antagonise a person with whom they sympathise. We ask you not to get carried away by these "effects", if they exist, and that your answers really reflect what you think.

(A) Rate with 1, 2, 3, 4 or 5 the following aspects of the course in which you have just participated (where 1 represents a very negative assessment; 3, neutral; 5, very positive)

1. Interest of the contents of the course
2. Coherence between the proposed objectives and the methodology
3. Classroom environment
4. Time-content relationship
5. Mastery of content by teacher

6. Clarity in teacher explanations
7. Teacher methodology for developing sequences
8. Teacher ability to increase my interest in inquiry-based science teaching
9. Learning scientific contents (to me)
10. Learning how to teach using and inquiry-based science teaching approach
11. Explanation of the specific objectives of the sequences
12. Achievement of the objectives of the sequences
13. Sequences of activities (structure, interest...)
14. Orientation (important question to be solved)
15. Adequacy of the sequences and materials included
16. Applicability of the sequences
17. Interest in introducing inquiry-based sequences in the classroom
18. Interest in putting into practice the sequences
19. Willingness to continue in the project
20. Degree of usefulness of the sessions
21. The way how the course has been developed
22. Overall assessment of the course

(B) Explain the obstacles (and possible ways to overcome them) that you might face when carrying out the innovation that inquiry-based science teaching would entail:

obstacles	Possible ways to overcome them

(C) Do not think now about your case and reflect on which factors do you think would influence when another colleague puts this way of teaching science into practice.

Appendix B

Semi-Structured Interview After The First Implementation Of The Innovation

1. What real obstacles/impediments do you come across when carrying out this type of inquiry-based teaching in your classroom? If we could work together to improve the aspects mentioned, would you carry out this type of teaching in your classroom?
2. Some of your colleagues, after finishing the training course, expressed the following factors or limitations that influence when carrying out the innovation: available materials, space, number of students or the engagement and involvement of the teacher. Do you agree? Still being the same limitations or have they changed after personally putting it into practice?
3. Do you think that these difficulties could be compensated with the learning reported by the students? Or, on the contrary, it does require to spend a lot of time and effort and the changes are not as good as expected?
4. What feelings have you had regarding the learning of your students? Have you noticed any progress in the students, between what they initially thought and what they think now about what they worked on? Or, on the contrary, do you think that it would have been better to work on it in the usual way?
5. What thoughts, sensations or feelings have you had as a teacher?
6. Do you find negative aspects regarding how you usually work with your students?
7. Do you find improvements compared to how you usually carry out your science classes?
8. Would you change any aspect of the sequence of activities carried out in your class? Any activity, grouping of the students (student organisation), way of formulating the initial questions, the scientist's notebook, or any suggestion that you think would improve the development of the sessions?
9. Suggestions, comments, doubts...

Appendix C

Newsletter For Parents

As you might be aware, several innovations have been taking place in your child's classroom over the past few months, can you briefly describe what this has been about?

How did you find out about it?

In relation to this innovation, have you noticed any different behaviour than usual in your child?

Appendix D

Items Section A: Teacher-Student Interactions	Teacher	
	Y	N
1a Teacher asks questions aimed at students to express their ideas		
1b Teacher helps learners to formulate their ideas		
1c Teacher gives students positive reinforcement on how to check their ideas		
2a Teacher encourages predictions		
2b Teacher involves students in the investigation		
2c Teacher encourages checking their predictions		
2d Teacher encourages and assists in collecting data		
3a Teacher asks students to present their findings		
3b Teacher asks students to match their conclusions to their results		
3c Teacher asks students to compare their conclusions with their predictions		
3d Teacher asks learners to try to give reasons or explanations for what they have found		
Items Section B: Student Activities	Teacher	
	Y	N
4a Students work on questions that they feel are their own		
4b Students make predictions		
4c Students participate in the research plan		
4d Data obtained allow students to test their predictions		
4e Students consider their results in relation to their questions		
5a Students collaborate when they work in groups		
5b Students engage in discussions about their investigations		
5c Students present their work to each other		
5d Students listen to others when they communicate results		
5e Students take notes on what they have done		

Appendix E

Semi-Structured Interview With The Teachers Involved After The Second Implementation Of The Innovation

1. You have carried out a teaching sequence twice that you did not do before:
   - How different has it been from the way you taught science before? (shallow/deep)
   - What is your assessment of this process? (negative/positive)

2. Throughout this process, what has been the most laborious for you? (preparation/appropriation time; materials for children; methodology; content; group management; . . .).
3. Next year you can decide whether to carry out this sequence in the same way or not, do you plan to do it like this again?
4. If you plan to do it again and you have told me aspects that have required personal effort, what makes you continue? Can you specify the reasons why this change is gratifying for you?

(After you answer openly, you will be shown a list of possible reasons -usually when you talk you can forget some of the reasons, even important ones-: (1) Increased learning of children (how do you know?); (2) Greater involvement of children; (3) They learn more things besides science: oral and written language, logical/mathematical thinking, . . .; (4) Children are more motivated/happy (what do you notice?); (5) They improve their way of reasoning; (6) Parents rejoice; (7) I like teaching science more than before; (8) My work is thus more creative; (9) I find meaning in what I teach (I don't give something because it "touches"); (10) A positive dynamic has been generated with my classmates around this project on science teaching; (11) The Management is happy with this change and encourages me to continue).

5. Next, we are going to show you a list of basic emotions so that you can evaluate them before and after the change, that is, we want to know how you have felt throughout the process: before, during (first implementation of the innovation) and after (after the second implementation).

Usual teaching

Excitement	Tranquillity	Fear	Pleasure	Tension	Worry
Frustration	Interest	Overwhelmed	Boredom	Curiosity	Confidence

Teaching by inquiry (1st time)

Excitement	Tranquillity	Fear	Pleasure	Tension	Worry
Frustration	Interest	Overwhelmed	Boredom	Curiosity	Confidence

Teaching by inquiry (2nd time)

Excitement	Tranquillity	Fear	Pleasure	Tension	Worry
Frustration	Interest	Overwhelmed	Boredom	Curiosity	Confidence

6. How did you feel the second time you put it into practice compared to the first? Have you had to change many things? Has it been easier?
7. As we said, this year, you have made the decision to continue:
   - To what extent do you think your peers have influenced your decision to continue? In what ways?
   - And the direction? In what ways?
8. We would like to know what has served you the most or has been most useful so that you have put it for the second or third time in your classroom.
9. We know that you were already a good teacher. Has what you have been doing contributed anything to you from a professional point of view?
10. Your experience is very useful for us to reflect on how to improve in other schools.
    - Do you think that any teacher could change in a similar way that you did? What conditions must be met for such a change to be possible? Why?
    - And the school, what conditions. . .? Is it an individual or collective issue?
    - So far, we have been working on a single sequence, what would it take for the change to extend to your entire way of teaching science? (After her open-ended

response) Would you be willing to put in the work necessary to make another sequence your own?

Now I am going to ask you about the sustainability of this innovation:

11. As you know, the sequences you have developed are part of a "sequence thread" (from 1st to 6th) in one of the large blocks of content ("the Matter").
    - Do you think that the change in science teaching in this block will last in the school? Why do you expect it to be so?
    - Do you think there is enough coordination to maintain the progression from 1st to 6th? Why do you believe that?

Appendix F

Structuring Problem (Origin of the storyline)	Usual Title/s	Titles in Interrogative Form of the Problematised Teaching/Learning Sequences	
How Are All Things Made Inside? How Are They Different? What Do They Have In Common?	Specific Properties	How are the materials different?	What material are these objects made of? Could they be made of others? (1st grade)
	Common Properties: Mass And Volume	Are all the things we see totally different, or do they have something in common?	Which weighs more? Which takes up more space? (2nd grade) How is the air? (3rd grade) How to measure the properties of objects (measure)? (4th-5th grades)
	Density	Are all the things we see totally different, or do they have something in common?	Which material is "lighter"? And "heavier"? (5th-6th grades)
	Electric Charge	Are all the things we see totally different, or do they have something in common? (Another general property: electric charge)	Is attracting pieces of paper a property of all materials? (5th–6th grades)
	Corpuscular Model	How are things formed "inside"?	What are gases (like air) "on the inside"? (6th grade)
	Chemical Change	How do you explain the changes or transformations that occur in Nature?	How to explain that there are changes in which substances disappear and different ones appear? (Suitable for Secondary Education)

Appendix G

Structuring Problem (Origin of the storyline)	Usual Title/s	Titles in Interrogative Form of the Problematised Teaching/Learning Sequences
How is the Sun path? Is it always the same? Does it change? Does it repeat itself? CAN WE USE IT FOR ORGANISE TIME AND SPACE?	Moon Phases	Does the Moon always look the same? (1st grade)
	Path Of The Sun	How do we see the Sun during the day? (2nd grade)
	Seasons	Does the Sun always rise in the same place? (3rd grade)
	Seasons	Do the days always last the same? (4th grade)
	Seasons	Is the Sun always the same high? (5th grade)
	Size And Distance. Sun-Earth Model	What shape and size are the Sun, Earth, and Moon? (6th grade)
	Sun-Earth Model	Does the Sun look the same from all places on Earth? (6th grade)

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