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Editors

Iterative Design of Teaching-Learning Sequences

Introducing the Science of Materials in European Schools

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Introduction

Dimitris Psillos and Petros Kariotoglou

Policy efforts in the European Union have emphasised the need to increase students' interest in science, enhance their understanding of scientific inquiry and stimulate their appreciation of the relevance of science to society and the connections between science and technology (Science Education NOW 2007). Design-based research in science education is a methodological framework for promoting innovations in terms of the new strategies, processes, tools and content that will be needed to support new forms of teaching and learning that, potentially, will contribute substantially to each of these goals. In the European science education community, this trend is materialised through the design, development, implementation and evaluation of teaching-learning sequences (TLSs), which are a medium-scale curriculum product covering a scientific topic. The current discussion related to developing TLS concerns the design principles used, the establishment and use of design frameworks, their empirical validation and iterative development. One way to make science relevant to society and enhance the connections between science and technology (Gago et al. 2005) would be to change the emphasis in science teaching from concepts to materials. Young citizens come into contact every day with natural materials and technological artifacts, such as wood, clothes, mobiles, CDs and hi-fi, which have very characteristic properties. The study of these materials, and their properties and structure, could increase young people's motivation, heighten their interest in and understanding of science and deepen their relation to technology. In order to study the above idea, we established several working groups, comprising science education researchers, content experts and experienced teachers, with a remit to

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design, develop and implement innovative TLS about some aspects of the properties of materials. A characteristic feature of our project was its focus on innovative approaches to introducing aspects of materials science at different levels in school education and on investigating partnerships between university researchers and school teachers. The members of the group brought together diverse expertise on a corresponding topic in materials science, the local educational context, the values and priorities of the curriculum and educational design and research as a mechanism for infusing and validating the development of educational tools. This volume reflects on the work of these working groups, clarifying the main ideas that guided their efforts but also reporting on the various forms of evidence that were used to monitor the process of iterative refinement of TLS in materials science. This volume includes a series of theoretical papers highlighting specific aspects of the participative design of TLS, some aspects of materials science and a set of case studies on the development and iterative evolution of six TLSs concerning innovative approaches to introducing various aspects of materials science in school. The combined collaborative efforts of experienced science education researchers and science teachers in using established principles and knowledge in order to solve teaching-learning problems in the domain of materials science are illustrated and documented. A TLS is often both a research process and a product that includes well-researched teaching-learning activities. Often, a TLS develops gradually out of several implementations, according to a cyclical evolutionary process enlightened by research data, which results in its enrichment with empirically validated expected student outcomes from the planned activities. The development of TLS has become the focus of several theoretical and empirical studies (Lijnse 1995; Duit et al. 1997). A special issue of IJSE focusing on several aspects of TLS was published in 2004. An extended review by Meheut and Psillos (2004) identified several empirical studies as well as the emergence of theoretical frameworks with somewhat different foci. Research related to the development of TLS in science education is in line with design-based research, which has been suggested as a general framework for promoting better connections between research and practice (Design-Based Research Collective 2003; Van Dijk and Kattman 2007; Leach and Scott 2005). Learning progression studies in science, which have been developed in the USA and elsewhere, fall also in this broad research line which attracts the interest of several researchers worldwide (Duschl et al. 2011). Designing a TLS is not a 'one-shot' activity but a long-term endeavour, one product of which is often an innovative content recontextualisation, which is different from those appearing in numerous textbooks and curricula worldwide (Andersson and Bach 2005). Such a process provides the means for linking research to innovation. However, the explicit and implicit assumptions and decisions that to a considerable degree affect the design and development of the corresponding teaching approaches are less widely treated and may not even be clearly presented. The construction of a teaching content adapted to students' minds seems to involve implicit expertise and special practices on the part of the researchers. It also involves, inherently, iterative design, which though applied in practice has not been extensively explored in the literature. The case studies in the book elaborate on the importance of iteration, mapping and supporting the modifications (frame for reporting modifications, documentation of specific elements as well as changes) beyond existing generalities looking at certain commonalities and rich variations between the different studies.

Another issue that seems to have drawn little attention in the literature is the role of various agents involved in the evolution of TLS. Our work has provided a unique framework for facilitating researcher-teacher collaboration at local and international levels. This involves a way of linking research to practice by combining different levels of expertise, an approach which is less investigated in the literature. The case studies elaborate on the role of researchers and teachers and their interaction in the design and particularly in the evolution of the TLS. All six TLSs are based on teaching science as a process of inquiry, which is now a widely spread paradigm in science education research (Minstrell and van Zee 2000; Duschl and Grandy 2008). Within this broader perspective, there are many strategies, such as modelling, hands-on investigations, design and development of artefacts and explorations based on digital technology (White and Frederiksen 1998). The sequences utilise existing modelling and simulation tools or have developed new applications in order to develop teaching approaches that adhere to the principles of inquiry-based science, active student engagement and collaborative learning (Chinn and Samarapungavan 2008). The case study reports draw on existing theoretical ideas on inquiry in various contexts and the need for contextualised innovation in a variety of school systems and existing practices. With regard to the content of the case studies, the book provides a unique assortment of papers that look deeply into aspects of materials science. Numerous materials and artefacts are used in everyday life, and there are important advancements in materials science which support the relevance of such a topic and warrant considering introducing it into school curricula. In the science education research literature, there is little discussion of the features and importance of materials science as a school topic. In this book, the various authors attempt to draw on certain important features of materials science from a disciplinary perspective and argue why it is valuable and stimulating for students to devote learning time to properties of materials and their applications. In short, the authors elaborate on important theoretical issues as well as aspects of the design and iterative evolution of a series of TLSs in a modern scientific and technological field which is socially relevant and educationally significant. The authors will elaborate on the design, refinement and validation of teaching-learning sequences as a mechanism for bridging research to practice. The CS reports show whether a group of teaching-learning sequences focusing on the same broad field, e.g. materials science, may provide powerful suggestions for introducing innovative subjects in a (inter)national context. They also elaborate common issues, so that the outcome of this endeavour is a truly coherent volume providing important insights into the factors affecting the evolution of TLS and introduction of materials science into schools rather than a set of disparate chapters. The first theoretical part of the book starts with a paper by D. Psillos and P. Kariotoglou, who provide an overview of developments and trends with regard to teaching-learning sequences and their classroom implementation, discussing empirical studies, and suggested design frameworks, methodological tools and approaches to describing the design of these sequences, their commonalities and differences and their relation to design-based research, as well as to learning progression. The authors argue that such frameworks are needed as intermediates between grand theories and content-specific design of teaching and learning, identify and elaborate on the common features and different foci of several well-known ones. They present and review empirical studies published in the last decade, arguing that in most cases their design is based on explicit principles, compared to earlier studies. However, these design frameworks are applied mainly by the groups who developed them. The empirical TLSs seem to be effective with regard to their aims. Though these TLSs have developed iteratively, the specifics of iterative cycles of research and development are not thoroughly discussed. This is an issue to which the chapters of the present book make a substantial contribution. In the second paper, K. Juuti, J. Lavonen and V. Meisalo argue that in order to address the problems arising from the school context, science education research has an essential role to play in diminishing the gap between educational theory and practice. They consider that design-based research aims to develop an educational innovation, i.e. a teaching-learning sequence that helps teachers and students in science classes to reach the objectives indicated in a curriculum. The authors emphasise the importance of engaging ordinary teachers in collaborative designing and testing of innovations, which is one way of taking serious account of the requirements of the school situation; they argue, therefore, that engaging teachers in shared design and testing activities would increase the likelihood of designed educational innovations being widely adoptable. In the third paper, D. Couso argues that over recent decades, an increasing amount of research has shown the importance of teachers' active participation in and ownership of innovation. As a result, different forms of school-university participatory approaches have been proposed, mostly around the idea of professional learning communities. Despite proving to be demanding for both teachers and researchers, such initiatives have been shown to be consistent with teacher development, empowerment and sustainability of efforts for change. The author further suggests that these truly participatory approaches are also particularly suitable within a design-based research (DBR) framework for science education research and innovation, being not only compatible but also desirable for both the quality and the validity of research results and products. However, as the professional development agenda that guides these fruitful collaborative scenarios can conflict with a DBR research agenda, this proposal is not exempt from tensions.

The second part of the book concerns aspects of materials science and technology and their educational adaptation. It includes two papers. In the first, E. Hatzikraniotis and Th. Kyratsi present a brief but comprehensive overview of the current challenges and advances in materials science as well as of attempts made worldwide to introduce materials science into secondary school curricula. Their paper is in two parts, the first presenting a short history of materials and an introductory review on the properties of materials and the second discussing educational perspectives and issues such as the connection of materials science (and science in general) with technology. The authors describe the approach adopted at preuniversity level as 'science of materials' rather than 'materials science'. In the science (or technology) of materials, technological applications are connected, as examples, with macroscopic properties of materials and, in some (rare) cases, with the microscopic models that are used for their explanation. This approach is found in many curricula and preuniversity textbooks. In the second paper, I. Testa, S. Lombardi, G. Monroy and E. Sassi present a research-based framework aiming at integrating science and technology from the perspective of content knowledge with emphasis on materials science. The proposed framework identifies a common science and technology core, namely, the scientific investigation and modelling of natural phenomena and the harnessing of basic physics in technological objects. The Model of Educational Reconstruction (MER) is adopted as a research-based route to elementarise science and technology contents in order to construct and adapt such common core for teaching. The authors also discuss some unresolved issues of the science and technology interplay in current trends of science education curriculum reforms and present the relevant aspects of Nature of Science and Nature of Technology that inform the framework. Examples from the properties of materials area, condensing aspects from both science and technology, are described to illustrate the enactment of the proposed framework. Some implications of this approach are also discussed.

The third part of the book consists of six case studies describing the design, development, implementation and evaluation of an equal number of teaching-learning sequences (TLSs) for teaching materials science in primary and secondary education. These case studies focus on the iterative process of TLS refinement. M. I. Hernández and R. Pintó describe the process of iterative development of a teaching-learning sequence on the acoustic properties of materials. The theoretical framework used to guide the design of the sequence structure, the selection of content and the pedagogical approach is described. This chapter also reports on the development of the teaching-learning sequence, carried out throughout two cycles of field testing to gradually improve the efficacy of the sequence in promoting better student performance. Throughout this iterative development, the writers identified the problematic aspects of the sequence during its classroom implementation, analysed the types of changes introduced to overcome students' and teachers' difficulties in using the sequence and outlined the critical reasons for those changes. A. Zoupidis, A. Spyrtou, G. Malandrakis and P. Kariotoglou describe an inquiry-based TLS for introducing density as a property of materials in floating/sinking phenomena, with emphasis on the process of the sequence refinement. They report that a real-life scenario increased students' interest and motivation, while in parallel it was a link between science and technology. The main aims of the TLS were to improve fifth graders' conceptual understanding of density and floating/sinking, as well as procedural and epistemological understanding related to control of variables strategy and the nature and role of models. In this paper, they focus on the processes of both design and refinement of the TLS. More specifically, they describe and justify the refinements from the first to the second implementation of the TLS, classifying them according to Pickering's model of scientific practice and to the origin of the data indicating the refinement. Most of the refinements refer to procedural and epistemological knowledge, while few concern the conceptual content of the TLS. In addition, the majority of refinements were guided by educational factors and only a few by scientific factors. The educational factor guides local-guided refinements, while the scientific factor guides holistic-open refinements. A. Loukomies, J. Lavonen, K. Juuti, V. Meisalo and J. Lampiselkä describe engaging students in active learning on the properties of materials around us through a design-based research approach for developing learning activities. In order to enhance students' motivation towards and interest in their science studies and promote learning about topics related to materials science, the writers organised an industry site visit and designed activities related to it. In design, the TLS follows the principles of the design-based research (DBR) approach. The iterative design process started with a review of relevant research literature and took place in four cycles. In each cycle, the TLS was tested with ordinary teachers, and problems in the procedure were revealed and rectified. The experiences of the participating teachers and students (age 13–15) regarding the TLS were examined with pre- and post-questionnaires and interviews. Differences between pre- and post-questionnaire data were analysed by t-tests, whereas data from the interviews were categorised according to motivation and interest theories. Based on the analysis of the data, the TLS was redesigned and refined after every cycle. This chapter focuses on the problematic aspects of the design that emerged during the implementations, the changes that were made and how the changes were justified based on the data that were collected during the process. I. Testa and G. Monroy describe the iterative design of a research-based teaching-learning sequence on optical properties of materials aimed at effectively integrating science and technology education. A common core relevant for both the scientific and the technological components was identified through elementarisation, inspired by the educational reconstruction model. The process was substantiated through a 2-year, three-phase research and development study involving four teachers and students aged 15–16 at 60 secondary schools in the south of Italy. Analysis of teachers' interviews and students' learning outcomes at each phase suggested changes which iteratively optimised the integration of the science and technology contents addressed. D. Psillos, E. Hatzikraniotis, M. Kallery and A. Molohidis describe the development and iterative evolution of a research-based teaching-learning sequence on the thermal conductivity of materials. The design and implementation of this TLS are outlined. Multiple sources of data from students and teachers were used. The paper presents the iterative evolution of this TLS, based on a reflective ex post facto approach focusing on the analysis and selective presentation of modifications and the relevant evidence. The results supported the effectiveness of modifications. The product of this work is twofold: a well-documented TLS on thermal conductivity and a model for the gradual introduction of innovative inquiry-oriented TLS in traditional contexts. N. Papadouris, C. Constantinou, M. Papaevripidou, M. Lividjis, A. Scholinaki and R. Hadjilouca describe a process of designing, developing and gradually refining a teaching-learning sequence (TLS) on the Electromagnetic Properties of Materials (EPM). The design of the teaching-learning sequence draws on principles from the frameworks of inquiry-oriented teaching-learning and learning through technological design. Combining these two frameworks was intended to lead to an instructional context that would likely sustain student interest for the extended time that is necessary to attain conceptual understanding of magnetic interactions and electromagnetic phenomena. Also, it was expected to facilitate the development of students' epistemological awareness regarding the interconnections and distinction between science and technology. The development process involved a series of six implementation-evaluation-revision cycles, with a total of 294 participants. In each implementation, they collected data on students' learning outcomes through various sources, including open-ended assessment tasks and student-constructed artefacts. After each implementation, they drew on the collected data, but also on the feedback provided by the teachers, so as to refine the teaching-learning sequence with the intent to enhance its potential to promote its targeted learning objectives. In this study, they illustrate how the empirical data collected during the implementation of the teaching-learning sequence could serve to guide its refinement. The authors report on particular instances in which the data on student learning outcomes led them to identify specific limitations of the teaching-learning sequence in terms of its facility to promote certain learning objectives, and they elaborate on the revisions we undertook so as to address those limitations. From the wealth of theoretical perspectives and the rich empirical studies, in the final chapter of the book, certain trends are traced, and open issues for further research are identified. We would like to thank all authors for their contribution to the book and the very interesting discussions we had during the course of writing, discussing and reviewing the chapters. We would also like to thank professors Hans Niederrer (Bremen), Vasilis Tselfes (Athens) and Pavlos Pantazis (Thessaloniki) for their work in acting as referees for some papers. Finally, we would like to thank Eleana Dalagdi for her patient and skillful work in preparing the manuscript.

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Part I
Theoretical Aspects

Theoretical Issues Related to Designing and Developing Teaching-Learning Sequences

Dimitris Psillos and Petros Kariotoglou

1 Introduction

In science education one notable line of research and development, aspects of which date back to the 1980s, involves the design, implementation and validation of short, topic-oriented sequences for science teaching in several subject areas, including optics, heat, electricity, structure of matter, fluids, respiration and photosynthesis e.t.c. Work in this area has developed gradually since the 1980s, more or less as a follow-up to empirical studies eliciting students' conceptions regarding a number of phenomena and concepts and to theoretical developments on teaching and learning as a constructive activity. Researchers have been developing various kinds of research-inspired instructional activities and approaches for improving students' understanding of scientific knowledge. One characteristic of these early attempts, which were inspired by constructivist theses, is the emphasis on conceptual learning rather than on teaching as well as on relying on general learning principles, such as that learners construct new knowledge based on existing acquisitions rather than on specific content-based models. Later on, issues like content analysis, didactical transpositions and enlargement of the aims of science education to include methodological, epistemological and social aspects of science came to the fore.

This trend falls within a science education research tradition in which teaching and learning of conceptually rich topics are investigated at micro (e.g. single session) or medium (e.g. a few weeks) level rather than at the macro level of a whole curriculum (one or more years). Although various terms have been employed in the

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past, the term teaching-learning sequence (TLS) is now widely used to denote the close linkage between proposed teaching and expected student learning as a distinguishing feature of such research-inspired subject-oriented sequences. A TLS is both an interventional research activity and a product, usually lasting a few weeks, comprising well-validated teaching-learning activities empirically adapted to student reasoning and often including teacher's guides with well-documented teaching suggestions and expected student reactions.

The state-of-the-art of research on TLS was described in a special issue of the IJSE by Méheut and Psillos (2004). The authors reviewed several empirical and theoretical studies and noted that TLS is a flourishing research sector, with several valuable empirical studies in various topics published over the last 30 years, and that both theoretical positions and questions or issues regarding the character of research into TLS have been brought to the attention of the European science education research community. Researchers tend to agree that this sort of activity involves the interweaving of design, development and application of a teaching sequence in a cycling evolutionary process illuminated by rich research data. Interest in design research has also spread to education research in North America, mainly under the broad perspective of Design-Based Research (DBR) (Design-Based Research Collective 2003; Kelly et al. 2008a). DBR has been advocated as an approach to educational research that seeks to provide means for developing innovative teaching and learning environments and at the same time to develop contextualised theories of learning and teaching. Besides, in another more recent research tradition Learning Progression (LP) works are carried out mainly in USA which deal with students' progression of scientific understandings in science and mathematics within the context of research-based content-specific artefacts (Dunkan and Hmelo-Smith 2009; Duschl et al. 2011). Few references to TLS appeared in DBR and LP studies and vice versa, however, a situation which has only recently started to change.

In this chapter, we attempt to provide an overview of recent developments and trends with regard to TLS and their empirical corroboration. We discuss theoretical theses, several suggested design frameworks, their common features and differences in foci. We have also identified recent empirical studies published in international journals and discuss whether they are based on a design framework or a set of explicitly stated principles, their structure, evaluation and effectiveness. We also attempt to identify certain emerging trends and open issues where further research is needed such the nature of iterative development.

2 Designing TLS: Grand Theories and Design Frameworks

Work in any design process involves drawing on several kinds of pertinent knowledge, including grand theories relevant to the problem (Tiberghien et al. 2009). In the case of TLS, various grand theories relating to pedagogy, development, learning, motivation, epistemology, history of the subject and sociology of education, and cognitive and social constructivism are possible sources or may afford general suggestions that can contribute to design principles. They have not much to offer, however, in designing teaching on a specific topic or providing answers to questions such as "how to deal with students' conceptual difficulties in explaining situation X" or "how to prompt them to relate scientific knowledge to evidence during experimentation in topic Y" (Lijnse 1995). Science education involves conceptually rich topics, complex relations between scientific theories and natural phenomena, multiple representations of standard scientific knowledge. This implies that replies to such questions cannot be based on general statements but warrant contextualising and interlacing of grand theories within the scientific domains. Accordingly, researchers have worked out frameworks to be used by designers as intermediates between grand theories and topic-oriented demands for developing a TLS. These published frameworks are presented below.

Starting from Freudenthal's position, Lijnse and the Utrecht group (1995) question the value of grand theories in providing specific answers for teaching and favour the development of modest, empirically valid proposals for teaching specific topics. Lijnse argues that the constructivist momentum is fading away and that the science education community is looking for a new paradigm, since the tenets and suggestions of constructivism, such as weak or radical conceptual change, were too broad to have specific implications for practice. Specific theories should focus on the identification of the problem, describe and analyse existing practices, identify aims, analyse scientific topic, take into account students, conceptions and reasoning, suggest and justify teaching scenario and learning pathways as well as possible learning difficulties and suggestions for handling them.

Lijnse puts forward a frame for developing *didactical structures*. Didactical structures include a scenario of successive steps, coherence between which is a major feature since details matter in envisioning and applying teaching. In this respect didactical structures differ considerably from normal text books, which include several inconsistencies. Lijnse proposes some guidelines for designing such teaching-learning situations to lead students to build freely the ideas we want to teach them. Great attention is paid to the motivational and meta-cognitive dimensions and to the learning on the part of the teachers made necessary by such an approach. Some general indications concerning conceptual development are given, with three suggested levels: selection of focus, transition to a descriptive level and, if necessary, transition to a theoretical level. It is proposed to deconstruct the teaching-learning process into five phases: motivation, question, investigation, application and reflection. In the context of developmental research didactical structures are empirically regulated and iteratively refined, starting from a scenario describing and justifying (a priori) the design of teaching-learning activities and the expected teaching-learning processes (Lijnse 1995; Kortland and Klaassen 2010).

In the "model of educational reconstruction" (MER) (Duit et al. 2012) the authors attempt to combine the German hermeneutic tradition on scientific content with constructivist approaches to teaching and learning. MER holds that clarification of science subject matter is a key issue if instruction in particular science content is to be developed. MER closely links considerations on the science concept structure with analysis of the educational significance of the content in question and with empirical studies on students' learning processes and interests. This model is based on an integrated constructivist view. On the one hand, the knowledge acquisition process is seen as an active individual construction process within a certain social and infrastructure setting, while on the other science knowledge is viewed as a tentative human construction. Results of the analysis of content structure and preliminary ideas about the construction of instruction play an important role in planning empirical studies on teaching and learning. The results of empirical studies influence the processes of educational analysis, elementarisation, and even the setting of detailed goals and objectives.

A frame earlier developed in mathematics education research is also useful for science education. It proposes guidelines for both designing and validating a TLS. In this general framework, Artigue (1988) outlined three main dimensions for a priori analyses: an "epistemological" dimension – analysing the contents to be taught, the problems they answer, their historical genesis; a "psycho-cognitive" dimension – analysing the students' cognitive characteristics; and a 'didactic' dimension – analysing the functioning of the teaching institution. This general framework rests on a strong model of learning by problem-solving. Thus, the a priori analyses are interconnected in order to precisely define 'problems' to be managed by students and to anticipate the elaboration of knowledge by students through these "problems". Comparing the cognitive pathways actually observed with those predicted can validate or challenge the hypotheses involved in the design of learning situations.

The *Two Worlds* frame was developed by the Lyon group, in order to inform the design of TLS by drawing on the epistemology of experimental sciences and on Vygotsky's theory of learning (Buty et al. 2004). The "two worlds" refer to knowledge and to learning; the frame thus makes a double categorisation of knowledge into everyday knowledge and physics knowledge, each offering ideas for describing objects/events in the material world which may be linked via modelling processes to distinctive theories/models for interpreting, predicting or explaining events in the material world. The researchers utilise the didactical triangle of knowledge, teaching and learning, and seek for grand theories related to each of these three poles. They refer to socio-cognitive theory for learning, and modelling for knowledge, but do not consider any theory of teaching, though they refer to Brousseau's theory of didactical situations. Modelling is treated as a foundation for scientific knowledge, and the physics classroom is viewed as a place where students are invited to participate in an educational community where one of the teacher's roles is to convey some of the knowledge and practices of professional physics communities. Modelling is suggested as a main activity for student learning. Two particular complementary design tools have been developed for informing the design of physics teaching: the Knowledge Distance tool, which potentially guides the framing and sequencing of the teaching content, and the Modelling Relations tool, which may guide the design of specific teaching activities at a more detailed level (Tiberghien et al. 2009).

The Leeds group draws upon the Vygotskian grand theory on meaning-making. Perspectives on personal sense-making and a realist ontology have been integrated with this grand theory to develop a social constructivist perspective on learning scientific concepts in schools (Leach and Scott 2002; Leach et al. 2010). The intermediate social constructivist framework brings together the social-interactive and personal sense-making parts of the learning process and identifies language as the central form of mediation on both the social and the personal plane. It draws upon socio-cultural approaches in conceptualising learning in terms of developing a new social language and in identifying epistemological differences between social languages, and upon evidence relating to alternative conceptions in clarifying the nature of the learning required by students in order to make personal interpretations of the social language of science. The *Learning Demand* (LD) is a design tool that was developed for identifying the conceptual aims of science teaching at a more detailed level. Another design tool, the *Communicative Approach*, focuses on classroom discourse. The verbal communication in the classroom is described in terms of two dimensions: authoritative/dialogic and interactive/non-interactive.

Andersson and Bach (2005) adopt a somewhat different perspective, thinking that: "… no general theoretical approaches, and recommendations for teaching that follow on from them, succeed on their own in this task. The answers must be sought in combination with content-specific research. The results cannot be deduced from the general approach….". Seeking to design effective TLSs that also advance educational theory related to a specific topic, they suggest that design work which aims to build insights into conditions that favour learning with understanding may or should develop "content-specific theory" (CST) for specific topics involving content-specific aspects (limited to the given topic), nature-of-science aspects (limited to school science), and general aspects (also valid outside school science). This research may be said to have two objectives. One is to design and test "useful products", such as teachers' guides and study material for students, which may be put into practice in various ways. The other is to contribute to the development of educational science; for example, understanding conditions for the learning of given topics in regular classroom conditions. Content- (or domain-) specific theories (CST) should focus on specific issues such as students' understandings or the nature of the topic, and general ones such as the role of the teacher as an agent of education and culture. They consider that designers who suggest a TLS may provide either a detailed sequence of activities and suggestions for teachers or outline some general principles and provide the relevant materials so that they themselves can develop relevant activities. As researchers in science education they also consider that science education should develop as an independent domain rather than a kind of applied psychology (Andersson et al. 2005).

Main assumptions and design features of the abovementioned frameworks (f/w) are presented in Table 1. The lines stand for the following:

Utrecht Group (Didactical Structures), Model of Educational Reconstruction (Several German Researchers), Goteborg Group (Content Specific Theory), Leeds Group (Learning Demands), Lyon Group (Two World), and Ingénierie Didactique (Artigue)

Table 1 Features of design frameworks

Frame-works/ groups	Promoting general or domain/topic specific theories	Content treatment and/or didactical transposition	Learning approaches	Teaching suggestions	Iteration	Core or detailed structure
Utrecht Group (Didactical Structures)	Specific, empirically valid	No information/ evidence, but implied	Adopts constructivist view (implied) – Conceptual change	Suggest scenario of five phases: motivation, question, investigation, application, and reflection	Iteratively refined	Rather closed, (implied)
Model of Educational Reconstruction (Several German Researchers)	No information/ evidence provided	Scientific content elementarisation Educational reconstruction of Content	Adopts constructivist approaches focus on students' learning processes Considers motivational factors	Instruction as product of interaction between content and student' conceptions but no details	Referred to many modifications but not explicitly to iteration	Rather closed (implied)
Goteborg Group (Content-Specific Theory)	Content-specific theory	No information/ evidence considers	Students' understandings and conceptual achievements –	Considers the teacher as "bearer of culture" no specific teaching suggestions	Appears to apply iteratively development but not explicitly	Propose both approaches, detailed structure or some core and general principles

Leeds Group (Learning Demands)	Propose design principles, not humble theories	Didactical transposition	Adopts social constructivism	Suggests a communicative approach for the teacher	Do not provide details of the iterative cycle	Rather open structure with elaborated examples and suggestions to teachers
Lyon Group (Two World)	Domain-specific theories and topic orientation	Distinction between everyday knowledge and physics knowledge Didactical transposition	Takes modelling as a main activity for student learning Social constructivism Focus also on treatment of learning pathways	Adopts Brousseau's theory of didactical situations, Suggests a teaching-learning scenario	Developed in three iterative cycles	Rather closed but in cooperation with teachers
Ingénierie Didactique (Artigue)	No information/evidence	Epistemological dimension: analysing the content to be taught, the problems they answer, their historical genesis	Psycho-cognitive dimension: analysing the students' cognitive characteristics	Suggests a teaching-learning scenario	No information/evidence	No information/evidence

The columns of the table correspond to the following characteristics:

- Promoting general or domain/topic specific theories: Stands if in the f/w is adopted the need of existence content-specific theories for developing TLS, or it lays on grand theories
- Content treatment and/or didactical trasposition: Stands if the writers adopt the analysis of the content to be taught, or even its didactical transposition as design feature to be taken into account
- Learning approaches: Identifies the prerequisites / theories of learning to which the f/w ascribes
- Teaching suggestions: Stands for the referred educational or teaching characteristics
- Iteration: whether the writers explicitly or implicitly adopt and refer to cyclical evolutionary process of TLS refinement.
- Core or detailed structure: Stands if the writers propose a detailed TLS or a core one

We discuss and compare certain features of the suggested design frameworks, noting that the following remarks reflect what we consider their relative emphases and do not imply that other aspects are ignored. In the framework of developmental research, problems for study are to be formulated by the students, with the help of the teacher. This appears to be more psychologically based, and the epistemic dimensions of scientific knowledge are not evoked as playing a determining part in planning a didactical structure. In MER we find content and psycho-cognitive analysis, but little discussion of educational constraints and the epistemic dimension. Learning Demands (LD) starts from students' conceptions, in order to delineate the distance from the content and nature of the knowledge to be taught. Though such an approach appears to apply a didactical transposition, in effect it takes into account scientific curriculum knowledge, implying that didactical transformation has already happened (Viiri and Savinainen 2008). MER takes into account and focuses on motivational factors in contrast to the LD framework, but without making any specific suggestions as to how such factors will be employed in design or how will they be evaluated. In *Ingénierie Didactique* the elaboration of problems to be treated is the responsibility of the researchers, is strongly linked to content analysis, and the epistemic points of view appear more explicit. *Ingénierie Didactique* focuses on a priori analyses: epistemological, psycho-cognitive (conceptions and reasoning) and "didactic" (educational constraints), while little is said about the social aspects of teaching-learning processes. The Two Worlds framework lays emphasis specifically on modelling from an epistemological and psycho-cognitive perspective, but not much is said about the role of teachers and contextual constraints. The Content-Specific Theory framework considers the epistemic dimensions of specific topics to be taught, the psycho-cognitive dimension and contextual constraints, but says little about motivational factors.

Overall, we consider that the aforementioned frameworks take into account and make for valuable and specific suggestions concerning the design of a TLS, paving the way towards principle-oriented research and development in this area. However, they provide few insights into the iterative process of developing a TLS.

3 Advancement in Designing Empirical TLS

Besides the theoretical elaboration of design frameworks, research in this area has been enriched by several studies that have focused on and empirically refined innovative interventions that keep up with essential characteristics of TLS. As with theoretical studies, several issues deserve discussion, such as whether these recent TLSs are based on a design framework or a set of explicitly stated principles, whether they are effective or not, whether they are closed or open, whether they are the result of an iterative design linear or a cyclical process of development. The empirical studies mentioned below were published in 2004 and later, following the review by Méheut and Psillos (2004). Though the list is extensive and several trends emerge, we do not consider that we have included all the studies published in well-known journals.

Two studies refer to MER as the framework for developing the developed TLSs. In the first study Komorek and Duit (2004) describe extensively and explicitly use MER to design studies concerning nonlinear phenomena. The themes of these studies were dynamic instability, structural stability, chaotic attractors and self-similarity. In the various studies mentioned in the paper the authors report interviews and interventions with small groups of students during which the interviewer probes interaction and discussions with students. Their method complies with design experiments allowing for studying students' conceptual change via analogical reasoning. Results concerned students' understandings of growth of fractals and chance. The authors suggest that although design experiment is carried out in a laboratory situation, it also shares major features of research in actual classrooms, and is therefore well suited for linking research and development in the first steps of designing a TLS, allowing for flexibility and in-depth study of students' learning processes. The suggested TLS appears to have a rather closed structure. There are descriptions of various attempts and modifications, but no explicit reference to the iterations process.

In a second study Fazio et al. (2008) developed a TLS about the concept of mechanical wave propagation and the role played by media in which waves propagate. The authors describe the design process with respect to MER and proceed to carry out an analysis of the content as well as students' models. This is a structured TLS centring on the relationships between observable phenomena, like macroscopic wave behaviours, and their interpretation and/or explanation in terms of the corpuscular characteristics of the media. The main focus is on students' representations of phenomena and on the cognitive strategies put into action in order to modify or support their descriptive and interpretative mental models. Data analysis is mainly based on qualitative methods. Results are discussed by pointing out the efficacy of strategies focusing on the process of constructing predictive conceptual models and by identifying the concept of "level of analysis" as different ways to look at the same phenomenon. From the results it is deduced that this TLS was effective with regard to the objectives pursued. There are descriptions of various attempts and changes but no explicit reference to the iterations process.

Tiberghien et al. (2009) present the development of a TLS in Mechanics for Year 10, which is based on their "two world" framework. One characteristic of this study is that the TLS has been developed cooperatively with teachers and after several trials of the activities and units. Another characteristic is that separate activities were evaluated with respect to the usability and relevance of resources for the teachers and their validity for students' learning, by using questionnaires or video analysis of students' work. In the paper these authors explain how they constructed tools (Knowledge Distance, modelling relations, semiotic registers) which they use for developing activities. During the implementation of TLS, students work with the suggested activities, make their proposals and draw their conclusion, which they discuss with their teacher who validates or not the constructed knowledge. The authors compare their TLS with the approach of the official curriculum and set out differences. For example, the curriculum introduces results achieved by force, whereas in the reconstructed content of the TLS the concept of action to describe interactions between objects in the world of objects and events is used. The authors describe an activity concerning level relationships between objects and events (the motionless situation in terms of action: where an objects acts) and an activity involving the relationships between theory/model and objects and events (a diagram of all the forces acting on the system of a motionless ping-pong ball under water). They also compare their TLS with another of similar design which refers to general and specific theories (Clement and Rea-Ramirez 2008). The authors conclude that both TLSs emphasise psycho-cognitive and epistemological themes, e.g., classification of knowledge in different categories, treatment of learning pathways, discussion of fine grain size and intermediate phases in students' learning, though there were certain differences concerning the epistemological perspectives. These two approaches to TLSs lead to different results. The argument goes that such a comparison is valuable for the development of domain-specific theories. As with other groups, this TLS is based on the design framework they have developed: it is fairly structured, is effective with regard to the activities and their validity, and appears to have been developed in three iterative cycles.

Leach et al. (2010) present an application of their LD framework and how the suggested tool called a design brief was used to establish and communicate knowledge in a TLS on the particle model of matter addressed to students aged 11–12. Specifically, the TLS focused on explaining why gases have mass and spread out to fill the available space. The goals were: reinforcing students' knowledge, introducing a single particle model, using the model, and supporting students' learning. They continued with pedagogic strategies, such as a formative assessment, an authoritative presentation of the content and its use, explaining properties of gases explained by the model, etc. The authors take educational constraints specifically into account and explain that the example is specific to the English curriculum and local norms. The TLS was developed in cooperation with teachers as a series of lessons, so that teachers could handle the teaching requirements. The authors analyse results from two classrooms, classifying their answers in four groups from underdeveloped to consistent use of the taught model. The authors consider that their TLS was relatively successful, and discuss the role of the two teachers who implemented teaching in different manners, one following the suggested lesson plans while the other made changes. Finally, they provide tables including a description of the context for the designed teaching and the specification of the content aims for teaching. This TLS is based on the framework the group has developed, as is the case with all the groups that have elaborated design frameworks. One interesting feature is that this TLS follows a rather open structure, with elaborated examples and suggestions to teachers rather than a structured series of activities. The authors discuss the relative effectiveness of the TLS but do not provide details of the iterative cycle.

Savinainen et al. (2004) describe an approach to designing and evaluating a TLS referring to Newton's third law. The design of the TLS draws upon conceptual change theory in a social context, the concept of the "bridging representation" as well as previous approaches to teaching the third law. Instructional design proposes social interactions between teacher and students as the teaching and learning activities are played out or "staged" in the classroom. Many instruments are used to measure the extent of student learning, and evidence is presented to indicate that the TLS leads to enhanced learning gains when compared to those achieved with an equivalent group of students. The authors take into account students' conceptions and outline the learning demands put forward by teaching. Following results from a pilot study there were improvements in the TLS, such as the application of symbolic representation of interactions (SRI) diagrams which were not used in the pilot study. The researchers have investigated the effect of this innovative tool (SRI) on students' understanding and application of Newton's third law as well as on contextual issues influencing the application of this law. Results showed significant differences between the experimental and the control (ordinary lectures) group in post and delayed post tests, while several students showed contextual coherence in applying their knowledge. Several design principles are stated by authors for this TLS, which has a rather closed structure. Iterative changes are not specifically described.

The next three studies are based on the CST framework developed by the Goteborg group. Andersson and Wallin (2006) developed a TLS on evolution, aiming to contribute to the development of educational science, e.g. understanding conditions for learning the given topics in regular classroom conditions. Their study is based on the CST framework. The authors describe aspects which should be taken into consideration in order for the students to improve their understanding, namely: analysis of the scientific content (conceptual structure, relations to other areas, social significance, etc.); explanation of subject matter if required, which may include a review of its historical development; report and analysis of research results concerning pupils' conceptions and opportunities for understanding, as well as results of any attempts at teaching the area; suggestions for goals in relation to the pupil's starting-point; discussion of conditions that promote learning of the given area with understanding. The TLS was implemented in several groups by different teachers. Pre tests, post tests and delayed post tests were used for evaluating students' conceptual achievements, which were better than with the traditional approach. Semi-structured interviews were also taken from the teachers.

The authors also applied their framework for developing a TLS on geometrical optics as mentioned in the paper by Andersson and Bach (2005). In this paper they describe the aspects of geometrical optics which should be taken into consideration in order for the students to improve their understanding. The TLS was implemented in several groups with different teachers. Pre tests, post tests and delayed post tests were used for evaluating the results which were better than with the traditional approach. One notable remark in this and the previous study is that the longer the teachers applied the TLS the better were the students' achievements. The TLSs have a rather closed structure, and were effective with regard to the objective pursued. They appear to have been iteratively developed, but there is no specific treatment of this process in the papers.

West and Wallin (2013) developed a TLS on sound transmission based on the DST framework, which was applied to students aged 10–14 years. One characteristic of this recent study is that the authors relate their work to design research. The main guiding design principle was that learning abstract concepts such as sound often involves an ontological shift in students' thinking, because to conceptualise sound transmission as a process of motion demands abandoning sound transmission as a transfer of matter. The results indicated a shift in students' understandings from the use of a theory of matter before the intervention to embracing a theory of process afterwards. The pattern described was found in all groups of students, irrespective of age, leading to the conclusion that teaching sound and sound transmission is already fruitful at the ages of 10–11. Moreover, the use of a TLS about sound, hearing and auditory health promotes students' conceptualisation of sound transmission as a process in all grades.

There are a number of interesting studies in which the writers do not follow specifically any of the aforementioned frameworks. Most of these proposals were developed along some design principles, and mainly on students' conceptions, and in some cases on conceptual change or the transformation of the content to be taught.

Guisasola et al. (2008) examine the didactic suitability of introducing a TLS for teaching the concept of magnetic field within introductory physics courses at university level. This TLS was designed by taking into account students' common conceptions, an analysis of the course content, and the history of the development of ideas about magnetic fields. The authors state clearly that TLS are products of research and development and should be based on design principles that refer to epistemological, psycho-cognitive, social analysis and should concisely follow them. They proceed to educational reconstruction of the content, develop and justify the design of teaching-learning activities in the context of curricula and time constraints. The evaluation is based on a combination of classical experimentation, by comparing the results with a control group using written questionnaires and qualitative analysis of recordings of class discussion. The results favoured the experimental group, showing that elements within the TLS helped students to reconcile an overall description with field analysis of magnetic interactions. Design principles and contextual constraints are explicitly stated, in this well-designed TLS, which has a rather closed structure with no reference to a specific framework. However, iteration is not specifically mentioned.

Sebastià and Torregrosa (2005) based their work on empirical findings about students' conceptions in order to develop a sequence about astronomical phenomena including day and night and changing seasons. They carried out conceptual and epistemological analyses of the content in order to adapt it to their subjects, who were student teachers. A data-to-model strategy was adopted, leading student teachers to the construction of a model of the planetary system. The TLS seems to be based on a structured sequence of activities, occupies 25 teaching hours, and had considerable learning results. However, iterative refinement and design principles are not specifically mentioned.

History of the subject continues to inspire several researchers. Theories and/or historical experiments have been utilised in a number of studies in addition to other design inputs. Hosson and Kaminsky (2007) describe the development, use and analysis of an educational tool inspired by the history of the optical mechanism of vision. They investigated 12-year-old students' reasoning about vision. Most of them explained it as the result of something coming either from the object or from the eye, while some of them think that light penetrates the eye only when they are dazzled. Such ideas can be found in the ancient and medieval history of science. In particular, the Ancients disagreed about the direction of vision until Alhazen opened the way to a consensus, arguing in the eleventh century that light could be a stimulus for the eye. The main tool is a short drama entitled "Dialogue on the Ways that Vision Operates", which refers to those historical elements, especially to the controversy over the direction of vision and Alhazen's ideas about light. This text was integrated into a TLS including a well-structured sequence of stages. Six couples of students aged 12–13 were involved in the empirical study. Their conceptual pathways were analysed against a detailed planned scenario. Results suggested that this TLS was effective in enabling students realise that seeing an object requires that the object sends out light into the eyes of the observer. Besides, the students identified themselves with the scientists portrayed in the drama and were involved in research processes, to formulate assumptions illustrated by a certain number of thinking experiments.

Two of the studies come from the Pavia group. The first of them (Borghi et al. 2005) is based on students' conceptions, and the authors propose a TLS designed to help high school students to understand the independence of the vertical and horizontal components of free-fall motion. Their approach is based on the combination of experimental activities from everyday phenomena and computer simulations designed specifically to help students reflect on the experiments and extend their analysis to wider physical situations. The logic of the experiments is based on Galileo's historical experimental investigation. This TLS was applied successfully with secondary school students as planned, but also with student mathematics teachers.

In the second study (Borghi et al. 2007) the researchers developed a TLS based on the use of microscopic models to link electrostatic phenomena with direct currents. The sequence, devised for high school students, was designed after initial work had been carried out with student teachers attending a school of specialisation for teaching physics at high school. The results obtained with this sample are briefly presented, because they guided the authors towards developing the TLS. The authors do not refer explicitly to any design framework or principles, though it is clear that the development of their TLS was based on students' ideas, historical development of the subject and the original works of Alessandro Volta. The TLS starts with experiments on charging objects by rubbing and by induction, and engages students in constructing microscopic models to interpret their observations. A structural model based on the particular role of electrons as elementary charges both in electrostatic phenomena and in electric current was proposed. By using these models and by closely examining the ideas of tension and capacitance, the students acknowledge that a charging (or discharging) process is due to the motion of electrons that represent a current. Both TLSs seem to be based on a structured sequence of activities and are illustratively described. Results concerning the effectiveness of the TLSs are not reported. In both TLSs the authors do not explicitly mention specific design principles apart from taking into account students' conceptions.

One interesting structural suggestion has been made by Besson et al. (2009), who clearly state that their TLS consists of an open proposal addressed to teachers rather than to students. This TLS is designed as an open-source structure, with a core of content, conceptual correlations and methodological choices, and a cloud of elements that can be re-designed by teachers. The TLS focused on friction and was based on a preliminary study involving three dimensions: an analysis of didactic research on the topic, an overview of usual approaches, and a critical analysis of the subject, considered also in its historical development. The TLS consisted of the following six parts: Introductory observations and experiences, definition of descriptive quantities and first qualitative relationships, phenomenological laws of static and dynamic friction, static friction and rolling, surface topography and mechanisms producing friction, and friction phenomena from the point of view of energy. The authors propose the use of structural models involving visual representations and stimulating intuition, aimed at helping students to build mental models of mechanisms of friction. The TLS was implemented with student teachers who afterwards taught it to secondary students after making appropriate adaptations. Results were positive for both groups. The authors conclude that: "The open source structure of the sequence facilitated its implementation by teachers, in coherence with the rationale of our proposal, thus starting an informal diffusion in real school environments".

We have reviewed several empirical studies which appeared in well-known journals in the recent years, identified key aspects of them and pointed out certain trends. One open question regarding the design approaches is whether the empirical works take into account or are based on the suggested frameworks reviewed here. We note that apart from few exceptions, works based on the suggested design frameworks reviewed in Sect. 2 tend to be applied by the groups from which they originated rather than be adopted more widely. For example, MER is used in three studies by researchers not participating in one way or another in the developing group. One explanation for this could be that the design frameworks involve craft knowledge which is an intellectual "property" socialised within the group which is used for taking design decisions. We suggest that this issue needs further elaboration in order for the frameworks to be applicable widely by researchers in designing their TLS. Another question is whether researchers present and discuss the theoretical and design basis of their works. We note that, apart from few exceptions, the researchers creatively apply various principles or the frameworks, making their choices more explicit in recent years than in initial works on TLS, e.g. specific features of students' ideas and difficulties as well as creative treatment of scientific content. In other words, there has been progress towards more 'principle-based' research and development since the previous review on TLS was published (Méheut and Psillos 2004).

4 Evaluation and Iterative Refinement of TLS

In this section we discus certain approaches concerning the evaluation and refinement of TLSs which are either theoretically espoused or empirically applied by researchers. Working with TLSs involves conceptualising and enacting interventions involving complex interactions and therefore empirically refining them to ensure that the work is of importance. Generally, researchers are in agreement that a TLS normally develops gradually out of several applications, according to a cycling evolutionary process enlightened by multiple types of research data. This process results in the enrichment of the TLS with empirically validated students' and teachers' reactions and contextual applicability. Such a design and development process tends to progress iteratively, which is widely recognised in design studies as a fundamental means for developing empirical validated interventions in complex situations. Kelly et al. (2008b) argue that "the core idea that provides most resonance in the design research literature is the idea of iteration, the capacity and knowledge to modify the intervention when it appears not to work or could be improved". Iterative development involves successive approximations of a desirable intervention. Each iteration helps sharpen aims and deepen contextual insights, and contributes to the outcome of design principles drafted, products improved and development opportunities for the participating team. Analysis, design and evaluation take place during or after each implementation. Analysis primarily features assessment of harmony or dissonance between the intended, implemented and attained learning. Its findings usually offer insights, guidelines and tips for design that target the closure of one or more gaps between the intended, implemented and attained TLS. These guidelines take the form of design specifications that will shape the content and structure of a TLS. As development continues, various products or principles may be partially or even wholly elaborated in a dynamic way. Revision of a design often involves taking account of aspects of the complex classroom situation that were not recognised in the original preparation of a TLS. At the conclusion of a design cycle, a TLS's stage of development influences the kind of evaluation activities that may take place, and vice versa.

Iteration is related to assessment and evaluation that is applied during or after intervention yet is not subsumed in them, since it involves several types of decisions related not only to learning but also to contextual factors and the viability of a suggested intervention. At the theoretical level, some of the aforementioned design frameworks only suggest, verbally or schematically, cycles of iterative development of a TLS which remain at a general level without any specific suggestions on how iteration should be carried out. Inspection of Table 1 shows that only two proposals refer explicitly to revisions via iterative cycles, (UG and LG2), two others implicitly refer to iteration (MER and GG) while for the rest two there are not any clues on the iterative process as a means for improving and adapting TLS (LG1 and ED). In a similar line Viiri and Savinainen (2008), by comparing MER and LD frameworks, note several similarities and differences but conclude that none of them relates specifically to iterative process.

We consider that design frameworks should be enriched or accompanied by specific suggestions at a finer grain size for the iterative process. At the empirical level most, if not all, reviewed TLSs are based on iterative development involving one or several cycles, showing that the development of a TLS is not based on data collection from a single implementation. Rather, it is obvious that a long-term design may involve different ways of refinement and empirical corroboration between successive trials within a TLS.

Often, feedback to designers is provided by evaluating students' conceptual learning involving several complementary techniques such as tests and interviews before and after teaching in line with the pre- post mode. The present review points out that continuous techniques such as video-based analysis of classroom transactions and students' conceptual pathways are also used in order to monitor the effectiveness of a TLS in contemporary and older studies (Méheut and Psillos 2004).

Such systematic documentation may take place before full classroom implementation in order to corroborate the TLS and its elements. Another means used specifically in TLS studies is the scenario as an evaluation tool. In both the "developmental research" and "ingénierie didactique" frameworks the concept of a teaching-learning scenario and the idea of comparing students' actual cognitive pathways to anticipated ones are elaborated. The same seems to apply for the "two world" framework. A comparison between intended activities included in a scenario and the realised pathways following classroom applications makes possible an empiric adaptation procedure, aimed at reducing deviations between the expected and the observed evolution in the students. Documentation and validation focus on whole TLSs, the units comprising them, even the several activities and their sequencing (Tibergien et al. 2009). This means that not only the final outcomes are evaluated, as usual, but also certain hypotheses relating to a finer "grain size". In other words a scenario may become a useful tool for checking the validity of 'local' hypotheses within a TLS.

With the exception of the Lyon group (Tiberghien et al. 2009), which attempts to reveal how the designed activities allow the students to become autonomous, most of the empirical studies do not pay much attention to non-conceptual knowledge, i.e. epistemological or procedural knowledge or students' motivation and attitudes (Loukomies et al. 2013). Studies of the effectiveness of TLS relate often to students' conceptual learning and do not take into account the multiplicity of factors related to the ecology of learning, the experimental activities, reading and writing, students' participation and collaboration. This means that many factors affecting teaching and learning during the implementation of a TLS are largely ignored. The study of such factors could add insights to the obstacles faced in enacting an intervention, e.g. students' difficulties in keeping notes or transcending contradictory experimental results, using a model, manipulating software, etc., in an inquiry-based teaching and learning environment.

5 Conclusion

Works concerning teaching-learning sequences, in one way or another, share an interventionist character, seeking to develop explanations, answers, useful and viable products, in response to emerging problematic situations, students' and teachers' needs (Sandoval and Bell 2004). The field is relatively new but promising since it combines both research and development features involving design issues, innovative products, theorising about students' learning treated in well designed and documented studies. From the present review we deduce a number of key themes which could frame the discussion and design of future TLS by researchers. Given the variety of theoretical and empirical approaches which this review has revealed the themes discussed below do not provide for a prescriptive framework for developing and evaluating TLS but rather issues to be taken into account by researchers in framing their work.

1. We consider that one issue to be taken into account by researchers in this field was and still is how to meet the dual goals of developing locally valued innovative interventions and create more generally usable knowledge (Andersson and Bach 2005; Bannan-Ritland and Baek 2008). Developing and studying a TLS can lead to two types of results: results in terms of effectiveness, which have a pragmatic value, and/or results related to scientific validity such as understanding students' learning processes, contextualising and testing learning theories and scientific content transposition. It goes without saying that the design principles or frameworks that researchers may take into account in developing their own TLS depend on contextual factors as well as their interests, and this is obvious from the survey of the empirical studies. In any case, we consider that for some researchers the aims of experimenting with a TLS can be more on the "experimental research" perspective and for others on the "production engineering" perspective as has been referred in the literature (Méheut and Psillos 2004). For example, in some studies reviewed here, like those by Savinainen et al. (2004) and Fazio et al. (2008), the researchers are trying to achieve precise descriptions of students' cognitive pathways and to test certain specific hypotheses that can be linked to a theoretical perspective of understanding cognitive processes and testing learning theories. Some other studies, like the ones by the Pavia group, are more oriented towards the creation of products than to the in-depth study of learning and understanding cognitive process. We consider that the products of these studies can be mainly linked to the pragmatic perspective of developing and applying useful and viable educational products in response to

conceived problematic situation(s) awaiting solution. Overall, the empirical studies reviewed here demonstrate the viability or effectiveness of these TLSs with regard to the objectives they pursue in the context of 'experimental research or engineering perspective' .

2. We consider that these two perspectives could, in fact, be complementary. In our opinion, to construct aims related to these two perspectives as clear as possible and to elaborate consistent methodological approaches for dealing with them in an adequate manner constitutes an important challenge for science education researchers with regard to future TLS. We suggest that the "experimental research" perspective and the 'production engineering' one are not contradictory and can be either attempted within different works or in a single piece of research. It would allow researchers to answer both the requirements they face: that of pragmatic value and that of scientific validity.

3. An overview of the frameworks mentioned in Sect. 2 suggests that there are certain differences in foci for managing TLSs. This is expected, because the authors draw on different grand theories in order to provide for models of such complex systems as real classroom interventions. Besides all frameworks draw on multiple sources of theories, a feature that is characteristic of works involving design of context-based educational sequences as well as of design interventions or products in other domains (Hjalmarson and Lesh 2008). On the other hand we note that a number of features are common to most if not all frameworks and this trend is an advance towards developing a consensus of the guiding conceptions for designing and investigating a TLS. Empirical works on students' conceptions are taken into account in one way or another as a major factor affecting design. In other words, works on TLS imply that use of, or investigation of, initial students' conceptions and/or their progression over the TLS at study is a key design feature. Concerning student' learning, the legacy of cognitive or socio-cultural constructivism is strongly influential – either explicitly or implicitly in most if not all reviewed frameworks and empirical studies providing the works on TLS for a powerful theoretical basis. Another pillar of designing a TLS is the treatment of scientific content. Despite the fact that these frameworks refer to different curricular contexts the usual scientific content is treated constructively in relation to the aims of instruction, resulting in innovations and divergence from empirically developed curricula content. Didactical transposition is more or less taking place in most empirical studies and is suggested in the design frameworks. In the present book one example of extensive discussion of such reconstructions relating scientific and technological content and skills is presented in the theoretical paper by Testa et al. (2016, this volume). We suggest that TLS provide for a powerful dynamic tool for investigating, critically analysing and creatively reconstructing a typical scientific content in order to adapt it to students' minds and learning demands set out by innovative interventions or usual curricula objectives.

4. What kind of theories may be developed in the context of future TLS and what their features may be is another open issue that needs further in-depth study by researchers. This is related to the character of theories and the elaboration of design frameworks. Cobb and Gravemeijer (2009) have argued that design research can

contribute to the development of 'humble theories'. From the TLS works there emerges, and is discussed by some authors, the quest for domain- or topic-specific theories in science education, which could correspond, in a way, to what Cobb and Gravemeijer have proposed from the DBR perspective. Andersson and Bach (2005) have developed domain-specific theories for optics and evolution which combine tenets from general pedagogical theory, epistemology of the subject and topic-specific research in each subject. These researchers consider that their approach might contribute to strengthening science education as an autonomous discipline. Lijnse (2010) suggests that the development of specific quality TLS or didactical structures (as he calls them) can be an endless task, but suggests that worked-out examples can provide teachers with useful insights. By contrast, Tiberghien et al. (2009) argue in favour of constructs and structures, such as modelling, at a phenomenological and theoretical level, transcending, as their argument goes, topic orientation since they are based on both the nature of science and a fundamental cognitive activity. However, Leach et al. (2010), who developed a social constructivist framework and related tools, consider that the time has not yet come for such humble theories and favour the development of design principles – or briefs, as they call them – by researchers as heuristics for developing TLS.

We consider that these are crucial yet open themes which need more study at a theoretical level by further elaborating design frameworks or principles and at empirical level by principled-based design. In any case, we suggest that the fruitfulness of theoretical proposals and related effectiveness of a TLS cannot be proved otherwise than by being enacted, applied and tested, since principles or frameworks are not empirically verified.

5. Actual teaching in normal classrooms is a constrained-based process affected by social and educational factors such as existence or not of digital resources, compulsory or not curricula, degrees of freedom of teachers to apply these curricula and/or to plan their teaching, time schedules, traditions and so on. TLS works involve innovative interventions, yet researchers apply them in usual classrooms affected by the contextual factors. We note that these factors are more or less implicitly taken into account in the empirical studies. In the design frameworks, these are explicitly taken into account only in the LD and CST ones. We consider that more work is necessary on this matter and specifically what and how contextual factors affected design decisions in the making and revising of a TLS.

6. The development of a TLS is not or should not be conceived as a 'one-shot' activity but a dynamic, long-term endeavour. Iterative development is proposed verbally or indirectly by diagrams in the design frameworks, yet suggestions on iterative processes remain at a general level. As we mentioned in Sect. 5, a TLS involves design work which by its nature is iterative and dynamic involving cycle of design-application-investigation-reflection-revision. The character and features of iteration are theoretically discussed in works related to DBR (e.g. Kelly et al. 2008b), which stress the approximate character of the interventions studies and the tentative conjectures guiding the development of both the design procedure and the product itself. In the TLS works discussion of the features of iteration is considered as self-evident rather than explicitly detailed. The design frameworks focus on the design

rather than on iterative development, notwithstanding as Ruthven et al. (2009) argue. At the empirical level there is lack of detailed description or guiding principles and tools for iteration, embedded conjectures in actual activities and the types of several multiple sources of decisions that, apart from students' learning outcomes, have shaped a TLS during cycles of iteration. Moreover, there is no discussion of iterative cycles and whether there was any retrospective approach tracing the history of the TLS in a reflective theory-based manner. We suggest that several issues remain open for further investigation by researchers concerning iterative development. For example what types of design decisions are or should be taken by researchers, what factors affect their decisions, what are or could be the results of such decisions. In any case, we accept that design decisions involve craft knowledge by developers, yet the more explicitly are discussed the better the design of TLS could be transparent. To this aim all the six case studies in this book provide detailed discussions of their decision-making process as well as the results of their decision thus illustrating in depth several aspects of these issues.

7. It is widely advocated in theoretical theses, and practically realised in TLS, DBR and LP works, that design and development are or should be a collaborative effort involving researchers, teachers and, depending on the case, other participants such as software designers. In this respect researchers attempt to deal with the widely accepted gap between "theory and practice" in educational research and development. Most prominently, they stress the crucial role of actively participating teachers, whose practical knowledge and experience is indispensable for implementing a TLS and testing the classroom viability of both the design and the product under study. While there is a growing body of research concerning teachers/researchers participatory approaches, in both the theoretically oriented and the empirical works the role of teachers is simply mentioned, briefly stated, or even taken for granted. That is not to say that the role of teachers was not taken seriously in the reviewed works, but this does not appear in the publications. For example, there is lack of discussion concerning the difficulties and tensions in giving up widely used but not appropriate tasks from the perspective of researchers versus teachers faced in such demanding situations as the decisions concerning the abandonment or change of the development of innovative materials.

Recently a trend has emerged towards the metaphor of the "teacher as designer" rather than the "teacher as reflective practitioner" in the professional development of teachers, which is influenced by extensive attempts by science educators to diffuse and apply inquiry approaches in classrooms. We consider that participatory approaches to developing and refining TLSs provide an appropriate setting for educating teachers in designing science teaching and learning instead of reproducing ready-made materials. The theoretical paper by Couso (2016, this volume) is a contribution towards this direction.

8. The role of teachers depends on the structure of the TLS as well as on contextual factors, previous classroom practices and educational culture. One relevant issue is how structured or open and adapted to the situation a TLS is. We distinguish several forms, from rather closed, structured TLSs to ones which develop a core and leave the rest in the teachers' hands. We consider that the rather closed ones are

more appropriate for systems in which curricula are compulsory while those involving a core are more appropriate for open and flexible educational systems in which teachers design and shape the content and materials for their teaching. It goes without saying that both approaches provide for an excellent material and intellectual resource to be used in educating both pre and in service teachers who are motivated to reflect on and perhaps reconsider their practice.

The present paper focuses on the review of theoretical and empirical works concerning TLS studies in science education. From a wider perspective, there are design works in other research traditions as well, like DBR and Learning Progression studies as mentioned in the introduction. Carrying out a comparative study of TLS with DBR and LP works is beyond the scope of the present paper since it would involve extensive review of such works in science education and in other fields like mathematics. Only certain features of LP and DBR works are discussed here in order to identify certain commonalities between these research traditions. DBR studies concern several fields such as mathematics, informatics and literature while TLS appear mainly in science education and LP in science educations and mathematics. A common feature of the studies in all three traditions is that they involve interventionist approaches, promoting better connections between research and practice, trying to develop contextualised theories of learning and teaching though certain LP works refer to existing curricula and students' learning progression within them. TLS and LP are contextualised within a specific curriculum, treating it as both a research process and a product, e.g. a book for teachers and/or for students. However, TLS time scale may be different from LP. TLS usually concern topic-oriented medium-level curriculum like electrical circuits spanning, for example, for a few hours up to several weeks. LP may develop in a year or several years in a specific theme like structure of matter. One main feature of TLS is the analysis and in some cases the didactical transposition of a scientific topic. LP is mainly concerned with the in-depth study and modelling progression of students' understanding of scientific knowledge (Songer et al. 2009). For LP studies assessment plays an important role. Some authors consider that LPs are or should focus on a few foundational disciplinary concepts, an idea that seems to revive in certain science educational cycles in USA (Dunkan and Hmelo-Smith 2009). DBR works aim at the creation of innovative teaching and learning environments, asking for new forms of teaching and learning, based on grand theories, instead of TLS and LP which ask for more humble theories for teaching and learning. We consider that empirical works in TLS to some extend focus more on the production of research-based products while learning progression of students towards scientific understanding occupy a considerable part of LP works, and theoretical developments occupy a considerable part of DBR studies. A unique feature in the evaluation of TLS studies as compared to DBR ones is the conceptual and epistemological analysis of the didactical transposition of scientific content in the light of research results on students' conceptions, the scientific and pedagogical coherence of the various activities in order to make for an improved TLS. Validation involves both wider applied methods like pre-pots testing as well as accounts of conceptual trajectories related to the demands of structured sequences of tasks. The discussion and specifically the theoretical reflections on iterative design are more extensive and elaborate in DBR studies than taken into account or published in TLS or LP studies. Case studies in the present book have made a step forward to providing insights in iterative design. Besides, the role of teachers in all three traditions is important in order to contextualise and embed artefacts in real classroom situations. Yet, the specific contribution of teachers' practical knowledge and pedagogical content knowledge in designing and developing such well-designed artefacts and their empirical validation needs further investigation.

Domain-based studies in the tradition of LP share with TLS a design-based approach and are flourishing providing for new insights content, instruction, assessment as is the case with TLS research (Alonzo and Gotwals 2012; Dunkan and Revit 2013). However, as mentioned in the introduction, overall, few references to TLS appeared in LP and DBR studies and vice versa, a situation which has only recently started to change and should lead to mutual interactions among researchers working in these traditions (Duschl et al. 2011; Ruthven et al. 2009) . The theoretical paper by Juuti and Lavonen (2016, this volume) which is based on DBR is an example of how one tradition may benefit from the other.

Work in TLSs provides a fruitful recent advancement of science education research and development of empirically validated products. This said, it is recognised that designers' and researchers' and teachers' craft knowledge about effective practices is valuable for providing contextually valid answers to specific didactical issues and questions. The advancement of the dialogue between grand theories, design frameworks, methods of empirical refinement and participants' craft knowledge is also considered to open new perspectives in addressing both the features of the design process and the expected products for improving science teaching and learning. One step forward could or should be to take more explicitly into consideration educational constraints, which are rarely explicitly managed or even reported. In other words we argue that researchers should make public the handling of contextual factors and particularly educational constraints. We believe that this is a difficult endeavour bearing on the feasibility of TLSs beyond small-scale innovation. This is also the case with managing social interaction in the classrooms, a factor that has only recently begun to be taken explicitly into account in the design of TLSs.

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Pragmatic Design-Based Research – Designing as a Shared Activity of Teachers and Researches

Kalle Juuti, Jari Lavonen, and Veijo Meisalo

1 Introduction

A well-known challenge for education is to implement the results of educational research in teaching. There are numerous approaches which engage in developing and validating educational innovations. In Europe, development and validation of research on teaching-learning sequences (TLS) has been a leading approach in designing topic-oriented sequences for teaching science (Méheut and Psillos 2004; Psillos and Kariotoglou this volume). In the field of learning sciences in the US, research in authentic classroom contexts has been conducted under the label design-based research (DBR) (Design-Based Collective 2003). DBR aims to develop an educational innovation which has the same meaning as teaching-learning sequences and helps teachers and students in science classes reach the objectives given in the curriculum. Our view is that the framework of pragmatism helps researchers organise the DBR projects (Juuti and Lavonen 2006). In this chapter, we elaborate how pragmatic framework ensures the issue of iteration, teachers' participation and decision-making process in designing TLS. These seem to be the key similarities of TLS and Design-based research (Psillos and Kariotoglou this volume).

Design-based research aims to develop educational innovations, i.e. TLS based on research literature in order to research teaching and learning in the context of educational innovations, such as educational technology. At the same time, the iterative process of designing and testing the designed innovation creates novel educational phenomena for teaching and learning research (Brown 1992; Design-Based Collective 2003; Sandoval 2004; Juuti and Lavonen 2006; Plomp 2013). However, teachers seem to be reticent to adopt educational innovations. The goal of our

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endeavour is to design TLS engaging in pragmatic framework that not only provides understanding of science learning but helps pupils successfully achieve the objectives of the school curricula. In order to achieve this goal, research into the way pupils learn is a necessary but insufficient condition. It is important during the designing process to take into consideration research-based knowledge on basic principles concerning the usability and diffusion of educational innovations. Our orientation to DBR is pragmatist: we value the teachers' (and pupils') actions and beliefs in the classroom. Further, we acknowledge the educational context as Psillos and Kariotoglou (this volume) emphasise.

In this chapter we aim to describe the design-based research from the point of view of pragmatism and focus on the issues of shared activities of teachers, researchers and other members of the design-based research team. The team includes all parties that are involved in the designing process (e.g. graphics designer, software coders). We emphasise the understanding of the teachers' world and priorities as an important component of any effort to design educational innovations. Our DBR activities are used here in order to illustrate that design solutions are typically designed for a specific national educational context and are likely to be difficult to use in other contexts not only due to language, but also due to different school practices and cultural traditions.

1.1 Pragmatism

Pragmatism is a philosophical tradition which was founded to provide an answer to the mind-body problem: how does our immaterial mind acquire knowledge of the material world? The classical pragmatists, Charles Sanders Peirce, William James and John Dewey, opposed the correspondence theory of truth and the view of knowledge as representation; they, and especially Dewey, focused on knowledge and the acquisition of knowledge within the concept of action (Rorty 2004; Biesta and Burbules 2003). Dewey viewed knowledge as an organism-environment interaction. "In brief, the environment consists of those conditions that promote or hinder, stimulate or inhibit the *characteristic* activities of a living being. --- A being whose activities are associated with others are a social environment. What he does and what he can do depend upon the expectations, demands, approvals, and condemnations of others. A being connected with other beings cannot perform his own activities without taking the activities of others into account" (Dewey 1916/1980, MW 9:15). In pragmatism, knowledge and action are seen to be intimately connected. We consider that in this situation, knowledge about science teaching and learning and teachers' and researchers' design actions as well as actions in the classroom are not separate. Knowledge about science teaching and learning emerges from the implementation of designed innovations in a classroom. Further, through reflection, knowledge is gained from experiences in the classroom. The outcome of the experiences and reflection is new knowledge as well as providing more intelligent teaching and learning environment design.

Based on a detailed analysis of Dewey's work, Rodgers emphasises that "the process of reflection is rigorous and systematic and distinct from other, less structured kinds of thinking. It has its origins in scientific methodology and, as such, includes precise steps: observation and detailed description of an experience, an analysis of the experience that includes generation of explanations and development of theories, and experimentation – a test of theory" (Rodgers 2002, p. 863). In order to broaden one's understanding of an experience, reflection needs to happen with others. In our case, the others are peer teachers and researchers.

When Dewey's view of knowledge as an organism-environment interaction is applied to design-based research in science education, knowledge can be seen as a construction that is located in the interactions of the teacher, the researcher and the learning environment. This environment includes classroom settings, social and psychological atmosphere, the pupils' motivation, their liking for and conceptions of the topic to be learned, as well as their goals. Knowledge of science teaching and learning manifests itself firstly in the way in which science teachers and researcher interact with and respond to actions in the learning environment. According to our pragmatist view of design-based research, designing changes for the learning environment in order to obtain new knowledge about science teaching and learning is a shared activity of researchers and teachers. This interaction is an active, adaptive, and adjustive process in which teachers and researchers seek to maintain a dynamic balance with the learning environment. Teachers and researchers are active participants in shared activities of re-designing the interactions that are intended to take place in the learning environment (cf. Biesta and Burbules 2003).

However, the pragmatic view does not assume that there is one real world that will be uncovered through scientific research. Pragmatists criticise the correspondence theory of truth. Any correspondence of a belief to reality can only be the reality under a particular description, and any such description is not ontologically or epistemologically privileged. This means that the truth of the researcher's utterance is highly dependent on context. Pragmatism avoids falling into solipsism, and into subjective and relativistic concepts of truth through the notion of intersubjectivity. Humans have similar experiences in the shared world. A science teacher and researcher individually constructs knowledge about science education and then co-reconstructs it in social practices through communication with other teachers and researchers.

Communication is a process for the mutual coordination of action. In educational innovation designing, it is *not* a process in which a teacher simply reacts to a researcher's initiatives, after which the researcher reacts to the teacher's reactions, and so on. Dewey's point here is that successful coordination requires that the teacher reacts to what the researcher *intends* to achieve with his or her activities, just as the researcher reacts to what the teacher intends to achieve with his or her activities. "Successful coordination requires that the partners in interaction try to *anticipate* the other's actions" (Biesta and Burbules 2003, p. 41).

Dewey uses the notion of *shared activity* in differentiating the situation where one "does not share in the social use to which his [or her] action is put" (Dewey 1916/1980, MW 9:17). In the situation of shared activity, one has "the same interest in its accomplishment which others have. He [or she] would share their ideas and emotion" (Dewey 1916/1980, MW 9:17). Engaging in shared designing activities, obtaining similar experiences in the classroom, and anticipating each other's intentions the researcher and the teacher could come to a stage where they share the same world. Further, through reflection new knowledge concerning teaching and learning is constructed. Here reflection with others needs to be understood more broadly than just discussion. In addition to reflective discussion, established educational research methods are needed when reflecting on designing and classroom testing experiences.

Following the Biesta and Burbules' (2003) interpretation of pragmatism we state that the situation where a researcher or a teacher does not know how to act is the starting point of the DBR process. There is the need to uncover the problem: What is the required change, what is the actual change in the teaching and learning environment, and what are the affordances and constraints? By answering these questions, researchers and teachers explicate the problem that needs to be overcome by means of educational innovation. At the same time innovation creates novel phenomena in order to analyse and understand teaching and learning better.

After explication of the problem, researchers and teachers interact with each other, decide on the main objectives to be pursued by the educational innovation, create a strategy for achieving objectives, and then test the strategy. Should a successful resolution be achieved, the point is not just that researchers and teachers coped, but that their understanding about the problem was sufficient and meaningful. Still, a description of how to manage the problem is not the representation of the "world out there", but a description of a relationship between actions and their consequences (Biesta and Burbules 2003).

2 Design-Based Research

We seek to describe features that characterise a design-based research approach to the development of educational innovations or artefacts and taking into consideration the pragmatic framework. We emphasise not only knowledge about teaching and learning, but the improvement of praxis as well. Therefore, the role of teachers in the design-research process is crucial. We reflect on our experiences on design-based research based on the project aiming to design the teaching-learning sequence *An inquiry-based industry site visit Materials Around Us* (Loukomies et al., this volume). We argue that the following three features determine the essential aspects of design-based research in this respect:

(a) An important objective of design-based research is to develop educational innovation as a shared activity of teachers and researcher in order to create novel educational phenomena and to help teachers and pupils to act (teach and study) better in a way that leads to learning;
(b) A design process is essentially iterative. It starts from the recognition of a need for change in teaching and learning activities. During the process, researchers

and teachers reflect on their experiences as well as on their habits, beliefs, affordances, and constraints. Design process leads to widely usable educational innovations;

(c) Design-based research renders novel knowledge about science teaching and learning through reflection on classroom experiences.

It is claimed that design-based research does not acknowledge the role of teachers in designing processes (Engeström 2011). Our contribution here is to show how engaging in pragmatism as a framework for design-based research and therefore emphasising the notion of shared activity will acknowledge the role of teachers.

2.1 Designing Generates an Educational Innovation

In design-based research, one of the aspects is widely usable educational innovation (cf. diSessa and Cobb 2004; Kelly 2004). From the pragmatic point of view, the role of designed educational innovation is to help a teacher to teach or students to learn better. This requires the teacher to play a cognitively active role. Teachers, ultimately create the learning environment by their actions in the classroom. We noticed that teachers who participated in the designing project of *An inquiry-based industry site visit Materials Around Us* (Loukomies et al., this volume) implemented the designed teaching-learning sequence in different ways. Thus, every designed innovation has intrinsic immaterial and undetermined aspects that constitute classroom action and can only be understood in accordance with the teacher's thinking. This aspect can be conceived of as the perceived affordance of educational innovation (Norman 1999). The teacher 'personalises' every innovation applied in teaching. In order to use it successfully, at some level, a teacher should understand and agree with the innovation. Based on our experience of the designing and teacher adoption process (Lavonen et al. 2006), it seems clear that it would be fruitless to design a brilliant or futuristic innovation with affordances that teachers are unable to perceive. If teachers cannot understand what the innovation aims to achieve, they would simply not adopt the innovation. Therefore, understanding a teacher's world is important in order to ensure that designed innovation is adaptive enough and adopting the artefact does not require too much adaptation from the teacher.

The challenge is how it would be possible to design an educational innovation that a teacher outside the design group would understand. In order to help teachers to understand and adopt the designed innovation, teacher guides are typically designed. After reading the teacher guide, a teacher is expected to understand the innovation. Following Dewey's (1916/1980, MW 9:20) argumentation an ordinary teacher, who hears or reads to rehearse imaginatively the activities in which the innovation has its use, mentally becomes a partner with those who used the designed innovation during the designing process. A teacher "engages through his [or her] imagination, in a shared activity".

During the daily practice of teaching, teachers are not very willing to read and learn things that they do not perceive as interesting. It has been established that it is difficult to develop science teachers' beliefs about teaching and learning (Tobin et al. 1994). This should be taken into consideration when designing an educational innovation. Teachers should think that the innovation in some way matches their own habits and beliefs. However, at the same time an innovation should have affordances that help teachers to teach in novel ways or support students in achieving curriculum objectives. Figuratively speaking, an innovation should be in the zone of the proximal development of teachers' habits and beliefs. This is a huge challenge for designers. In practice we have found it difficult to categorise what constitutes an innovation. As in the case of the industry site visit (Loukomies et al., this volume), there is very open ended innovation that requires teachers designing efforts.

2.2 Design-Based Research Is an Iterative Process

Engeström (2011) has criticised the design-based research process for its linearity: "starting with researchers determining the principles and goals and leading to completion or perfection. This view ignores the agency of practitioners, students and users. It seems blind to the crucial difference between finished mass products and open-ended social innovations" (p. 602). While engaging in pragmatism, the process of designing educational innovations takes seriously into consideration the agency of teachers and students (Juuti and Lavonen 2013). Further, an educational innovation is open-ended; it is not a finished mass product expected to be used in just one way in the classroom. Designed TLS can be characterised to have open source structure (c.f. Besson et al. 2009).

Taking seriously into consideration the educational context as emphasised by Psillos and Kariotoglou (this volume), and reflecting based on the ideas of pragmatism, one of our earlier design-based research projects started in the context of national core curriculum renewal. It had been decided by the Finnish parliament that physics and chemistry would be introduced as a new subject into primary school at grades 5–6. Earlier, subjects like environmental and natural studies had very little reference to physics or chemistry. Indeed, we as researchers and teachers in the field did not really know how to teach physics at early levels. However, our design-based research project aimed to create a web-based learning environment in order to help teachers to start teaching physics at grade five (Juuti 2005). In the project, one primary school teacher was the corresponding author or the manuscript author of the learning environment. The very first drafts of the learning environment were tested in the classroom. From the research point of view, one leading goal of the project was to determine appropriate learning goals for beginner level physics.

The first design task was (and is in general) to find answers in the available literature. The analysis focuses not only on pupils' learning, but also on teachers' habits and beliefs as well as aspects that constrain possible actions, and physical and cultural affordances that enable actions.

Loukomies et al. (this volume) argue that it is not possible to explicate the models of pupils' conceptions and learning or produce educational innovations without research. Norman (1999, 41) argues that "cultural constraints and conventions are about what people believe and do, and the only way to find out what people do is to go out and watch them – not in the laboratories, not in the usability testing rooms, but in their normal environment". This means that at the very beginning of the design-based research project, teachers need to be engaged in designing and the innovation needs to be tested in actual classrooms.

In the beginning, researchers and teachers generally only have a tentative strategy by which to manage the problem. The key issue in design-based research is that before designing, researchers and teachers should accept the uncertainty of their strategies and they should be ready to change, sometimes completely, their original tentative strategy. This emphasises the search for dynamic balance through iterative designing and testing phases. Established benchmarks and patterns of design (e.g., ISO 13407:1999; Clements and Battista 2000) help designers to plan their own unique design processes.

In order to develop teaching, one important aspect of design-based research in the context of science education is that not just researchers or designers, but also 'ordinary' teachers, outsiders to the design team, people who have little knowledge about the designed innovation and its educational theory background, are able to adopt and apply it in their teaching. Therefore, it is important to understand the intended user teachers' habits and beliefs, or, in other words, to make an effort to share in the teachers' worlds. In the case described by Loukomies et al. (this volume), several teachers with different backgrounds and different responsibilities were involved in the design process. One teacher, for example, was an expert in materials science and had begun his doctoral studies in this field. He designed laboratory activities in order to learn models of materials. Teachers had also participated in professional development courses. They designed their unique implementations by making industrial site visits. During the professional development course we acquired information about what kind of activities the student book and teacher guide – designed in the project – would promote in teaching.

At the beginning of the DBR project, Loukomies et al. (this volume) used a case study approach to collect data. During the project, researchers evaluated learning outcomes and the development of motivation by means of questionnaires There were in addition many methods to support reflection, including unstructured group discussions, semi-structured interviews and video recordings (Loukomies et al., this volume). Thus, evaluation employed multiple methods, as Bell (2004) has proposed. The main goal in testing the designed educational innovation is the coordinated communication between teachers and researchers. Designing and evaluation of educational innovation is the shared activity of researchers and teachers. Throughout the process, researchers help teachers to articulate the experiences gained whilst teaching. In this way the individual-level experience is transcended, and knowledge about teaching and learning is constructed. The recordings of interviews and discussions were later subjected to more detailed analysis.

The design-based research process is consequently abductive, and employs practical reasoning. While testing the designed innovation, researchers and teachers recognise the situation P. Their reflection focuses on 'guessing' what action Q in the environment E caused the situation P. If, however, the teachers' (and researchers') intention was to create a situation P' and after reflection (data analysis and literature reviewing) they believe that action Q' would cause the situation P', then the design group will make changes E' to the innovation that are believed to help obtain the action Q'. This is the core of the iterative process of design-based research. Bell et al. (2004) have introduced what they call *compelling comparisons* as an approach to evaluate different versions of design solutions. According to them, compelling comparisons test hypotheses (Q, Q') about learning embedded in the design solutions. Therefore, in regard to iteration in features of design frameworks, our approach of pragmatic design-based research engages explicitly in iterative process in design educational innovations, i.e. TLS. Different iteration cycles provide different educational knowledge.

2.3 Novel Knowledge

The key issue in educational research is to acquire new knowledge which could support practitioners who are able to act better and achieve the objectives of the curriculum in a more versatile fashion. Designing, producing and testing processes offer various kinds of experience. Edelson (2002) differentiates the knowledge acquired in these processes as prescriptive or descriptive. Knowledge about the designing process and the properties of a design solution is prescriptive. These prescriptions provide an example of the successful process and product. Design-based research offers the opportunity to acquire knowledge about learning. This type of knowledge is descriptive. Edelson (2002) calls knowledge acquired during the designing process design methodologies, design frameworks and domain theories. He distinguishes between two types of domain theories: context theories and outcome theories. Context theories are context-specific and outcomes are designed to be more general. Bell et al. (2004) do not see an important distinction between prescriptive and descriptive principles. Instead, they propose four levels of topic knowledge, namely general cognitive principles, meta-principles, pragmatic pedagogical principles and specific principles. Similarly, diSessa and Cobb (2004) introduce four types of 'theories' that design-based research produces.

During the DBR project (Loukomies et al., this volume), we received three kinds of new knowledge. Firstly, this chapter is a report of a deeper understanding of successful designing process; it reports on the importance of engaging teachers in the design-based research process. Secondly, the project offered prescriptive knowledge on how it is possible to integrate industrial site visits, learning by reading and writing, as well as inquiry learning in the school laboratory. Thirdly, the project provided information about pupils' interest in science.

Even though we have emphasised the aim of widely usable educational innovation, we would like to stress that our goal is not to produce perfect or best-selling innovation, a critique of design-based research scholars raised by Engeström (2011). Engaging in a pragmatic frame, we believe that when teachers and researchers design and evaluate educational innovations together, it is possible to obtain more credible knowledge about science teaching and learning. Further, – at least in optimal situation – it is plausible that innovations improve practice.

2.4 Aspects of Credibility

Discussion whether design-based research is research or development has been going on for some time. In order to treat design-based research as a branch of educational research rather than as development efforts, credibility aspects need to be explicated. We propose two levels to evaluate the credibility of design-based research. Firstly, design-based research typically uses mixed methods in its information enquiry. Thus, evaluation has to be based on the requirements of each methodological approach. The iterative design process produces large volumes of feedback data, and classroom evaluation can be seen as a process of validation. It provides evidence collected from teachers, students, the design group, and external evaluators during the implementation. Applying standard research techniques, it is possible to acquire credible information concerning teaching and learning in specific situations and contexts. Secondly, design-based research assumes that useful feedback can be obtained through evaluation of the quality of the designed artefact, its novelty and usefulness (Juuti and Lavonen 2006). During the project, it should be shown that something new (educational innovation and knowledge) (see Loukomies et al., this volume) has been produced, and based on testing and revising it improved teaching in certain contexts. One important goal of design-based research is that it should be possible to widely adopt the designed innovation. Thus, it is more adequate to discuss whether we have transferable vs. generalisable research outcomes. Transferability is the ability to apply the results of research in one context to another similar context. An important aspect of transferability is the extent to which a study invites readers to make connections between elements of the study and their own experiences. Furthermore, the popularity of an innovation reflects its implementability, adoptability, and possible impact on school practice. These are possible aspects by which to evaluate novelty and usefulness. DBR scholars are responsible for giving a detailed account of the iterative DBR process, and researchers need to be especially careful when they make re-designing decisions. They need to show explicitly why and on what grounds a change in an artefact was required, and why the researchers believed that this was the right way to proceed.

3 Discussion and Conclusions

In this chapter, we have clarified our view of the essential features of design-based research and reflected design-based research within a pragmatist framework.

We propose that there are three essential aspects that constitute the design-based research framework. Firstly, design-based research projects produce an *educational innovation*, i.e. Teaching-learning sequence that introduces a novel phenomenon in teaching and learning and is applicable to a wider audience than just the correspondence group. Secondly, the process of design-based research is essentially *iterative*: this emerges through the parties' mutual coordination of action which seeks a dynamic balance for weakly understood goals. Thus, the first prototype is seldom appropriate. In one sense, the documentation of revisions increases trustworthiness; during the project, designers and teachers learn something new. Thirdly, design-based research offers *new educational knowledge* to help teachers (and researchers as well) act better; in other words, it supports students in achieving the objectives of their learning in a more versatile way. Thus, a DBR project creates a teaching and learning situation through the use of designed innovation. Without innovation the new environment for educational research does not exist. We have followed these three principles by engaging teachers in designing and evaluation activities. Designing is a shared activity between teachers and researchers. Therefore, pragmatic design-based research could answer both requirements that science education researchers confront: practical value and scientific validity as Psillos and Kariotoglou emphasised in their opening chapter (this volume).

We argued here that a pragmatic framework helps design-based research scholars to direct their actions. Specifically, the pragmatic view of truth emphasises the relationship between a teacher and a designed innovation. Based on our experiences (e.g. Loukomies et al., this volume), the contribution here is the pragmatist interpretation of the aspects of design-based research. The Pragmatist interpretation of DBR emphasises the designing of educational innovation as the shared activity of teachers and researchers. We conclude that via teachers' and researchers' collaboration in designing, it is possible that each stake holder in a design-based research process understand more deep the complexity of science teaching and learning.

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Participatory Approaches to Curriculum Design From a Design Research Perspective

Digna Couso

1 Introduction

In the recent literature of educational reform, diverse collaborative experiences such as teachers' professional networks, partnerships and communities are being widely discussed as "our best hope" for sustained and substantive school improvement (DuFour 2007).

Arguments in favour of these participatory initiatives relate them with powerful educational ideas such as the bridging of the research to practice gap (McIntyre 2005); the increase of teachers' professional development and improvement of teaching practice (Darling-Hammond and McLaughlin 1996; McLaughlin and Talbert 2001, 2006); the emergence of positive and productive school cultures (Bolam et al. 2005; Reeves 2006) and the improvement of students' results (Sparks 2005; Vescio et al. 2006). More importantly, these initiatives have been discussed as effective regarding the achievement of certain sustainability (Fullan 2005; Stoll et al. 2006). From our viewpoint, this makes them a particularly interesting approach for curriculum design projects.

In spite of this, most curriculum innovation is done with none or very superficial teacher participation. More surprisingly, even in contexts that emphasise the role of teachers' in the collaborative design of curriculum materials, how this participation is organised is generally disregarded (Handelzalts 2009). Particularly interesting examples of this inconsideration of the organisation of the participation of teachers in curriculum design are design research frameworks such as Design-Based Research (DBR) or Teaching Learning Sequence (TLS) research. Although within these design and research frameworks collaboration with practitioners is a defining

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characteristic (Design-Based Research Collective 2003; Wang and Hannafin 2005), the importance given to the organisation of this collaboration in educational settings is minimal and, as discussed by Psillos and Kariotoglou (chapter "Theoretical Issues Related to Designing and Developing Teaching-Learning Sequences", this volume), quite often unreported. Knowledge coming from research on genuine participatory approaches, such as the community framework, is not generally used to enlighten researchers in the structuring of these scenarios.

The argument of this paper is that, as a consequence, the quality of the teaching and learning materials designed, the research results obtained and the possible sustainability of the experience in a design research study are potentially diminished. This situation could reverse: the design research approach is compatible with and can benefit from the inclusion of ideas from well-known constructs such as the professional learning communities (PLCs) framework. For instance, practical ideas such as how the active participation of teachers in the design team can be supported, how the necessary teacher learning and development can be achieved, how teacher ownership and leadership can be promoted along the process and how the process should be set up so that it can continue after the initial input is finished, will be discussed. As a result, a participatory approach to curriculum design from the design research perspective will emerge in the course of the paper.

In the following paragraphs, these ideas are elaborated. Starting from the justification of a more participatory orientation to educational change, participatory frameworks will be presented as the privileged sites for teacher learning and development within a socio-cultural and situative view of both processes. A description of the characteristics that make PLCs a good framework for participatory design research will follow. Finally, problems and tensions arising from the combination of these two challenging frameworks will be discussed.

2 Traditional Curriculum Innovation in Science Education: Forgetting that Teachers Matter

When thinking about curriculum innovation in science education, what generally comes to mind are new research-based policy documents or teaching-learning materials which, either as small-scale attempts or as part of a broader reform agenda, try to bring to the school new contents, tools and pedagogical approaches. However, we know from research in educational reform that purely top-down, product-oriented attempts to change the classroom by just flooding the system with new ideas and materials generally "fall flat" (Fullan 2001). Within these contexts, reforms are adopted only superficially and implementation fails, producing minimum classroom change.

Implied in any science education innovation that focuses on *delivering* educational ideas and curriculum materials to teachers and schools is a simplistic, technological and analytical conception of educational change. Within this so-called input/output view, it is expected that the "built-in" didactical knowledge in the teaching and learning materials or policy documents will be used by teachers in an almost straightforward manner. As van Driel and colleagues point out when analysing the standard process of curricular innovation, "*the role of teachers in the context of curriculum change usually has been perceived as* '*executing*' *the innovative ideas of others*" (Van Driel et al. 2001, p. 140).

Seeing teachers as direct 'executors' of others' innovative ideas is problematic in terms of the disempowerment of these professionals. Even more problematic, however, is the fact of perceiving the process of putting into practice an innovation as the simple enterprise of executing it, as if direct transmission of knowledge and competence was possible. In addition, this 'execution' is considered *quasi*-universal, the innovative curriculum materials expected to be used in a similar way, whatever the particular teachers and schools. In short, it is forgotten that teachers, actually, matter (OECD 2005).

But why do teachers matter? Literature signals at least two main reasons to involve teachers in curriculum innovation by understanding it as a complex endeavour the quality of which depends on the quality of two inter-related processes: curriculum development and teacher development (Penuel et al. 2007). The first refers to the importance of teachers' participation in curriculum design to enrich it with practitioners' views and guarantee its plausibility. The second refers to the fact that curriculum innovation often needs supportive teacher development to be implemented adequately.

2.1 Why Do Teachers Matter? Innovation as Teacher Development

That teachers are crucial for any innovation attempt is not new in the science education field. The pioneering work of Black and Atkin (1996) analysed different reform processes in science education, finding better results associated with teachers' active participation in all phases of innovation: from planning of reform and designing of materials to assessment of outcomes. Teachers' involvement in curriculum change was not only perceived as important in ethical, motivational or emotional terms. The more problematic issue regarding traditional science innovation was related to the critical transformations that teachers made to the rationale of the innovations when adapting them to their classroom contexts, which could distort them in significant ways (Pintó 2005; Reiser et al. 2000). Even highly motivated teachers who had received training on the innovation were shown to implement the new curriculum without adequately taking into account most of its didactical "critical details" (Viennot et al. 2005). The essence of the innovation was either not grasped or not able to be put into practice satisfactorily. Ogborn (2002) discussed this issue, underlining the need for teachers to have real *ownership* of innovations in terms of mastering the science education knowledge involved, and for science education researchers to seriously take this need into account.

Interpretations for these findings can be found in the literature on teacher learning, change and development. First, to implement curriculum innovations teachers need to learn, educational change being essentially a matter of teacher development (Ball and Cohen 1999; Fullan and Hargreaves 1992). Second, this learning is complex and needs to be carefully planned and supported, taking into account what we know about teacher learning and professional development.

2.1.1 How Do Teachers Learn? A Situative and Socio-cultural View

As a field, we know very little about what teachers learn within their workplace and the multiple professional development opportunities in which they participate (Wilson and Berne 1999) due to the *"scattered and serendipitous"* nature of teachers' learning (Borko 2004). However, for Bransford and colleagues "*an explosion of cognitive research in the past 20 years has resulted in a rich body of knowledge about learners and learning in general and in Mathematics and Science in particular*", which applies to teachers as well as to their students (Bransford et al. 1999, p. 6).

According to these authors, some general principles summarise what we need to know about learning regarding teachers: (1) what learners already know influences their learning; (2) learners acquire new knowledge by constructing it for themselves; (3) the construction of knowledge is a process of change (addition, creation, modification, refinement, restructuring, rejection); (4) learning happens through diverse experiences. The first three ideas reflect a certain "constructivist consensus" that emphasises the importance of teachers' beliefs, knowledge and practices in educational change (Haney et al. 1996; van Driel et al. 2001). The fourth idea refers to the complexity of professional learning, signalling the potential for learning of diverse professional activities.

The constructivist consensus above mentioned views learning as a private, internal and individual process (Engeström 1994). Since the 1980s, however, one can find in the literature support for the idea of learning mediated by the culture and social environment in which the learners interact. Influenced by the works of Vygotsky (Wertsch 1985), a growing recognition of the role of socio-cultural aspects in learning has permeated the way science learning is perceived, both for students (Driver et al. 1994; Solomon 1987) and for teachers (Bell and Gilbert 1996; Engeström 1994).

Linked with this socio-cultural view of learning are *situated cognition* theories. Within this framework, knowing is a matter of active engagement in the world, of participation in the practice (the pursuit of valued enterprises) of a particular social community (Wenger 1998). Learning, then, is *"a process of enculturation or individual participation in socially organised practices"* (Hennessy 1993, p. 2).

In a social theory of learning, then, learning is considered both social and situated (Putnam and Borko 2000). On the one hand, this means that we learn from others, and with others, in our mutual interaction. This fact gives teachers' professional cooperation a crucial role regarding teachers' learning, highlighting the importance of the organisation, facilitation and guiding of such collaboration. On the other hand, learning (cognition) is situated: it happens in the situations or in the social activities in which we are involved, it happens through experience (Barab and Duffy 2000; Engeström 2001). In the case of teachers it can happen in continuous professional development (CPD) initiatives, but also while teaching, while discussing with colleagues, while mentoring, while doing action research or, as it is argued in this paper, while actively participating in curriculum design.

2.2 *Why Do Teachers Matter? Innovation as Curriculum Development that Needs Teachers*

The participation of teachers in curriculum development is not only important in terms of, as above mentioned, allowing teachers to learn the essence of the innovation rationale, but also to reframe this innovation rationale so that it becomes truly feasible. Their participation helps to signal the criticality of those aspects which are outside the "Zone of Feasible Innovation" of teachers in their actual school contexts (Rogan and Grayson 2003). These are those aspects that are challenging to bring into practice even for teachers which are theoretically aligned with the innovation. Despite the fact that for research purposes it could be interesting to explore what happens in particularly challenging scenarios, within an evidence-based view of curriculum innovation its actual feasibility should set the limits to what it is proposed from research as desirable curricular changes.

Teachers' participation in curriculum design, if adequately orchestrated, does not only contribute to the feasibility of innovations but to their richness. The adaptation of theoretical designs into teaching and learning materials that make sense in the real classroom can enrich these designs with teachers' practical knowledge (van Driel et al. 2001; Lijnse 2010). To Ogborn (2010), even the challenges of local adaptation should not be interpreted as a negative situation, as *"good educational solutions often capitalise on local problems and constraints, turning what looks like a difficulty into an opportunity"* (p. 71). In fact, despite the tensions between researchers and teachers that could emerge along the process, collaborative curriculum design is generally reported by researchers as a fruitful experience that produces a sound curriculum (Reiser et al. 2000).

2.2.1 The Role of Research Knowledge in Curriculum Innovation

Crucial in this discussion on the importance of and the extent to which teachers should participate in the curriculum development process it is the role we give to science education research knowledge in curriculum design. While many curriculum designs are presented as research-based, implying that, as a field, science education research has produced enough knowledge to guide designing efforts, some authors hold a more sceptical position regarding what research can do for curriculum design. For Ogborn (2010) research more than often points to educational problems rather than proposing direct solutions. As a consequence, he considers we should be more *"modest about what research can contribute to curriculum development, and admit that there are cases where insight, intuition, experience of teaching and deep knowledge of the subject are at least equally valuable sources of ideas about how to teach"* (p. 76). Despite the creative act of designing curriculum, if research-based, *"should rest on a solid background of didactical knowledge and experience"* (Lijnse 2010, p. 81), scholars have urge caution to limited views that understand this knowledge-for-teaching as only theoretical, formal and university-based, undermining the importance of the practical knowledge that researchers and teachers can contribute.

A different framing of the question, however, is not whether research knowledge should be considered the main knowledge source or not for curriculum development, but what sort of research approach is more helpful for this particular purpose and what is the role of teachers within this sort of research framework. This is the reason why in this paper we focus on the sort of research that is done with this practical purpose in mind, that is, the research that is purposefully closely linked with curriculum design and development, to explore teachers' participation.

3 Design-Based Research, Research on Teaching Learning Sequences and the Participation of Teachers in Curriculum Design

According to the critical review of Linjse (2010), curriculum development in Science Education needs a new sort of research, as from current research approaches *"hardly any agreed-upon didactical knowledge has become available for teachers or curriculum developers"* (p. 85). Domain-specific research-based guidance in a form that can influence practice is necessary (Millar 2010). This research agenda implies a shift from focusing on big theories and general curriculum changes to a focus on didactical micro/meso-knowledge and particular design alternatives: on concrete knowledge and constructs about how to teach a rich conceptual topic X.

As discussed in detail by Psillos and Kariotoglou (chapter "Theoretical Issues Related to Designing and Developing Teaching-Learning Sequences", this volume), the science education research linked to the development of TLSs and research with a design approach such as DBR are examples of research frameworks that follow this agenda. TLS research has been defined as research that focuses on designing instructional materials both as innovations and research tools to address "*specific topic-related learning problems*" (Méheut and Psillos 2004, p. 515). DBR refers to research that designs and enacts interventions in an iterative manner to produce humble theories (Cobb et al. 2003). In common to both approaches is the production of knowledge and constructs useful for research-based curriculum design, such as design briefs (Leach and Scott 2002) or didactical structures (Lijnse 2010).

Both DBR and research on TLSs are research and development approaches that have been highlighted and extensively described in other chapters in this book (see chapters "Theoretical Issues Related to Designing and Developing Teaching-Learning Sequences" and "Participatory Approaches to Curriculum Design Within a Design-Research Perspective"), and have been used as the methodological frameworks for most of the studies presented here (see chapters "The Evolutionary Refinement Process of a Teaching Learning Sequence for Introducing Inquiry Aspects and Density as Materials' Property in Floating/Sinking Phenomena", "Design and Development of Teaching-Learning Sequence (TLS) Materials Around Us: Description of an Iterative Process", "The Iterative Design of a Teaching-Learning Sequence on Optical Properties of Materials to Integrate Science and Technology", "The Iterative Evolution of a Teaching-Learning Sequence on the Thermal Conductivity of Materials", "DeDesign, Development and Refinement of a Teaching-Learning Sequence on the Electromagnetic Properties of Materials". In all of them a research-based TLS is designed and refined in an evidence-based manner, through its iterative implementation, to produce not only a good educational product but new knowledge in the field.

Taking into account 1. the importance that, according to previous sections, should be given to participatory curriculum development and 2. the suitability of TLS/DBR research to inform curriculum design processes, the discussion in the following paragraphs will be devoted to the role given to teachers' participation in these research frameworks.

3.1 Teachers' Participation in DBR and TLS Research Frameworks

Initial scholars within the framework of "design experiments" referred to addressing complex problems in real contexts with practitioners (Brown 1992; Cobb et al. 2003). In more recent definitions of DBR, the collaboration with practitioners is highlighted as one of the bases of DBR research "*[DBR is] a systematic but flexible methodology aimed to improve educational practices through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings, and leading to contextually-sensitive design principles and theories"* (Wang and Hannafin 2005, p. 6). The importance and particularly the way to organise this collaboration is emphasised in DBR with a developmental orientation, which is highly situated and problem-driven (Nieveen et al. 2006).

The emphasis given by DBR to the real context of teaching and learning, its aim of directly influencing actual practice from analysis of real teaching and learning problems and producing high-quality realistic teaching-learning materials, and finally its focus on explicit design principles that need to be shared with teachers for an adequate implementation, all situate this approach close to a participatory framework where varying degrees of teachers' participation are possible (McKenney et al. 2006). How to motivate, support and empower teachers in these participatory contexts, however, is not generally clarified in the literature in the field, neither what specific theories researchers use to organise them (if any).

The recognition of importance in contrast with absence of detail regarding the participatory aspect of general DBR is also found in science education design research. An example is the wide body of research on TLS, described in detail by Psillos and Kariotoglou in chapter "Theoretical Issues Related to Designing and Developing Teaching-Learning Sequences" (this volume). Although within this framework, many authors explicitly recognise that *"designing a complete teaching sequence is a collective work in which both researchers and teachers provide important competences"* (Buty et al. 2004, p. 588), how this collective work is organised and for which particular purposes is generally unreported. Researchers refer to this superficially, mentioning teachers' collaboration without making explicit if they are referring to active participation in the design according to design principles, collaboration in the re-design of researchers' draft designs or mere adaptation to local needs of ready-made designs. There are also few references to "who" these teachers are: while in some cases it can be deduced that participating teachers are those already aligned with the didactical ideas of the researchers due to a previous history of education and collaboration, in other studies teachers are more representative of the general teacher population. As Meheut and Psillos (2004) noted in their well-known review of the field, TLS researchers generally do not specify how they take into account contextual factors apart from some typical descriptive information.

A possible explanation for this lack of explicit attention to the participation of teachers in research on TLS could be a bias that, according to Leach and Scott (2002), is found in the field: the fact of attributing improvements in learning to the sequence of activities and treatment of content in the TLS, "*giving little explicit attention to the teacher's expertise in staging those teaching*" (p. 115). The authors claim that the role of teachers during the implementation of the innovative TLS is generally not made explicit.

On the whole, despite the lack of detail regarding the participatory aspect of DBR and TLS research, within these design-based frameworks the importance of achieving a fruitful collaboration with teachers is generally acknowledged (Psillos and Kariotoglou, chapter "Theoretical Issues Related to Designing and Developing Teaching-Learning Sequences", this volume). Making these "design research"[1] approaches more participative, however, has epistemological and practical implications.

[1] As discussed by Psillos and Kariotoglou (chapter "Theoretical Issues Related to Designing and Developing Teaching-Learning Sequences", this volume), DBR and TLS research are two design research frameworks that, despite having many aspects in common, belong to different research traditions that scarcely refer to each other. In the following, we will refer to "design research" as encompassing these and other research traditions (such as developmental research or didactical engineering) that emphasise the need for a close link between design and research efforts, due to the fact that for the matter of our discussion (the organisation of the participatory culture that could better support those efforts) the distinction is not needed. This does not mean, however, that there are no differences and specificities of each of these research frameworks that should be taken into account when discussing other aspects.

3.2 Participatory Design Research: Epistemological Implications

Teachers' participation in curriculum design from a design research perspective is challenging for both teachers and researchers. This is due to the crucial role research knowledge has in this scenario as both the seed and the result of the design and refinement process. In these initiatives it is necessary to bring relevant research results from previous research to teachers, enrolling them in a collective process of understanding, enriching, adapting and using this knowledge in their practice. It is also necessary to produce new knowledge, by inquiring the new practice and interpreting the results obtained.

As a result, the traditional separation between science education research or "knowledge production" and its implementation or "knowledge consumption" is challenged. The traditional distinction between *knowledge-for-practice* (formal and universal knowledge, already known in the field, university-produced, which is learned in teacher education initiatives) and *knowledge-in-practice* (the practical and tacit knowledge embedded in the action of expert teachers, which is acquired through reflection) becomes problematised, as none of these definitions can capture the sort of knowledge needed and produced in participative curriculum design from a design research perspective. What these contexts require is a new relationship between knowledge and practice that gives importance to the teachers' and researchers' use and generation of theoretical and practical knowledge that is both locally meaningful and globally relevant.

This sort of knowledge has been referred to in the literature as *knowledge-of-practice* (Cochran-Smith and Lytle 1999). Within this new epistemology of educational knowledge, the focus is shifted towards the process of problematising what we know and do in the science classroom by systematic, intentional and collective inquiry. From our point of view, this idea is of renewed interest in the design research framework, as truly participatory design research implies problematising, both from the researchers' and practitioners' perspective, the knowledge needed, used and produced. This is problematising the knowledge embedded and missing in current practice, the design principles behind the new research-based curriculum designs and the processes and outcomes of the evidence-based inquiry and refinements done.

Understanding the nature of the research endeavour within design research as a sort of collaborative problematisation of current knowledge and practice has important consequences. For instance, the collaboration with teachers becomes relevant even to decide the goals and means of the research effort, as "*interaction with practitioners is needed to gradually clarify both the problem at stake and the characteristics of its potential solution*" (van den Akker 1999, pp. 8–9). This implies a partially "negotiated" research agenda between researchers and practitioners which, as it will be later discussed, could set limits to the sort of research topics that can be undertaken within this framework.

3.3 Participatory Design Research: Practical Implications

Collective problematisation of research knowledge usage and generation imply an enlarged notion of the teaching profession. To be involved in curriculum development from a design research perspective, either as co-designer, re-designer and local adaptor of pre-existing designs or as self-designer in teacher-centred or school-based teacher teams, demands an understanding, use and production of fine-grain research results (design theories) that is not typical of other curriculum design perspectives. This implies new roles, expertise and responsibilities from teachers. In the partially analogous classical metaphor of the "teacher as curriculum designer" (Clandinin and Connelly 1992), this is referred to as "a change of profession" that implies dilemmas and it is not made by teachers without difficulty.

The challenge to teachers is so important that it cannot be attained by teachers alone, and supportive structures that are far from trivial are required. As a consequence, researchers' role has also to change. Their challenge is now to design (perhaps even to research) with (instead of for) teachers. This implies the generation and facilitation of collaborative environments in which teachers' knowledge and practices emerge but also where the necessary teacher learning and development takes place, so that a new high-quality curriculum (enriched with practical and theoretical knowledge) is designed, trialed and refined in an iterative manner, and so that new knowledge in the field is identified, shared and produced.

The complex environments described imply necessarily more than mere cooperation between teachers and researchers. They could be framed within professional development, as there is *"a natural synergy between curriculum development and teacher development [which] can provide more fruitful research and development opportunities"* (McKenney et al. 2006, p. 74). This is referred to as the tertiary output of design research: contribution to the professional development of participants. This contribution can be of importance, as to involve teachers in collaborative design of curriculum materials is, in fact, a way to comply with the features of effective teacher professional development (Voogt et al. 2011) and promote teacher learning (Davis and Krajcik 2005). In spite of this, the role of design research in teachers' development has been underestimated and underportrayed. Professional development is usually seen as a challenging pre-condition for success (Dede 2005), rather than something to be acted upon. In addition, as an endeavour that combines innovative curriculum design, teacher professional development and high-quality research, participatory design research should not be conceived short-term: it requires intensive and long-term collaboration between researchers and practitioners (McKenney et al. 2006).

Taking into account all considerations, the creation and maintenance of these complex scenarios cannot be technically prescribed. They require the establishment of a particular working culture among researchers and teachers able to trigger, develop and sustain the design, development and research effort. In many ways this working culture resembles that of a community of mutually supporting professional learners and/or inquirers. In the following section this notion of professional community will be unveiled, discussing its potential for participatory curriculum design in design research.

4 A Route to Participatory Curriculum Design for the Design Research Approach: Ideas from the Community Framework

The community framework has been extensively discussed, developed and researched in the literature, as the strategic locus for teacher professional learning and development (Mclaughlin 1994). Different notions have emerged[2]: communities of practice (Barab et al. 2002; Little 2002; Wenger 1998); discourse *communities* (Engeström 1994; Putnam and Borko 2000); *on-line communities* (Barab et al. 2001; Lieberman and Wood 2003); *teacher communities* (Grossman et al. 2001; Thomas et al. 1998) or *professional learning* communities (Hargreaves 2007; Stoll et al. 2006), among others. In common to all these it is a tendency to focus on the idea of community as an ongoing venue for teacher learning and development that has an influence in classroom and school change.

Seeing the diversity of notions and proposals, it is not surprising that authors *"urge caution about the profligate uses of the term community"*, which is at risk of losing its meaning (p. 6, Grossman et al. 2000). Therefore, we focus our interest in a singular construct, the well-spread notion of *professional learning community* (PLC),[3] with the aim to identify which characteristics of this framework help the orchestration of effective teacher participation in curriculum design from the design research perspective.

4.1 PLC as a Model for Participatory Approaches to Curriculum Design

PLCs are the most well-known and used community scenario for teachers and school development (Hargreaves 2007). However, the rationale behind the PLC framework is not new, having its routes in early ideas of enquiry, reflection and

[2] Here we include both authors who use the notion of community of practice to explore existing groups and those who intentionally define, orchestrate and analyse particular community constructs to favour particular purposes.

[3] Although most of the literature refers to PLCs that are school-based and school-wide communities, we do not adopt this view here because it narrows the field of action and thought. A school-based community is not a situation that is feasible, or suitable in every school system, for every school level or for all schools. We prefer to use, then, an extended notion of community which, however, struggles to maintain the idea of aiming for a systemic approach, at the possible systemic level that can be achieved in each educational scenario.

self-evaluation of teachers and schools by Dewey; ideas of teachers as classroom researchers and curriculum developers by Stenhouse; and the conceptualisation of the teacher as a reflective practitioner by Schön (Bolam et al. 2005; Stoll et al. 2006), among others.

In the literature about PLCs different definitions and proposals have emerged, always suggesting "*a group of people sharing and critically interrogating their practice in an ongoing, reflective, collaborative, inclusive, learning-oriented, growth-promoting way, and operating as a collective enterprise*" (Stoll and Louis 2007). Five key characteristics are proposed for PLCs: shared values and vision, collective responsibility, reflective professional inquiry, collaboration and a central focus on group, as well as individual, learning (Bolam et al. 2005), which are also characteristics of science education PLCs (Fulton et al. 2010).

The above-mentioned characteristics emphasise that PLCs are not just communities, but communities of and for professional learning. In a PLC, learning is both the tool for and the goal of change: students' learning is fostered by participants' learning in a practice-embedded way. This standpoint is crucial, as the emphasis is not on mere community (collegiality and group cohesion) but on doing so to improve teachers' professionalism and change of teaching (Little 2002; McLaughlin and Talbert 2001; Visscher and Witziers 2004).

A professional community of learners has particular goals, values and belief systems, but also discourse structures. Taking into account that in the PLC framework the professional learning pursued comes from closely examining relationships between teaching and learning (Blankstein et al. 2008; Darling-Hammond and McLaughlin 1996; Little 2003; Nelson 2009; McLaughlin and Talbert 2006), a privileged discourse is that of a community of reflective practice, inquiry or participatory research. To do so, the community relies on the development of a *discourse genre* in which constructive discussion, querying and criticism become the norm. What is pursued is a culture characterised by an *inquiry stance* where questioning, evidence-informed, reflective and self-evaluative attitudes and action are promoted (Cochran-Smith and Lytle 2009).

A model for a participatory approach to design research inspired in the PLC framework is, then, one that recognises the importance of a focus on learning and the establishment of an inquiry culture for curriculum design, implementation and refinement. It has to involve teachers in an on-going professional community for which professional learning is necessary and in which teachers and researchers work collaboratively, bringing closer educational research and practice (both using existing research and contributing to existing research), with the aim of improving students' learning by iteratively generating improved curriculum designs (such as TLSs, learning trajectories, action protocols, etc). Researchers here can be guiders, facilitators and/or participants of the community, depending on teachers' expertise, the educational system, the scope of change to be achieved, the previous tradition of collaboration and other factors. Therefore, there is a need for fitness for purpose regarding the organisation of the participatory approach.

Whatever the case, the implementation in practice of the PLC framework presents challenges and difficulties (Stoll et al. 2006; McLaughlin and Talbert 2006;

Wells and Feun 2007), some of which are particularly challenging when the PLC is organised from a DBR approach. Examples are the issues of trust, rhythm and leadership. These play an underestimated role on the quality of the initiative: the acquisition of a real inquiry stance, the promotion of teacher development, the achievement of impact in terms of students' results and the sustainability and scalability of the experience. The following sections are devoted to the discussion of these aspects.

4.2 The Role of Trust and Rhythms in Participatory Approaches to Curriculum Design

It is commonly agreed among scholars in the field that trust is the single strongest facilitator of professional community (Stoll and Louis 2007) and, from our viewpoint, also for any other truly participatory approach. Activities common in PLC, such as pedagogical discussion, enquiry on students' results, team-teaching, classroom observation and feedback, etc. are demanding tasks that require teachers' confidence within a safe environment. Undoubtedly, there is risk involved for the participating teachers: of becoming object of evaluative judgement on their knowledge and abilities; of self-exposure when sharing personal views about pedagogy or subject matter; of losing autonomy when negotiating future action.

Despite its importance, trust is very difficult to construct, in particular when there is a previous past of untruthfulness, either among teachers or with researchers. Trust is fragile and needs personal in addition to professional involvement, for which neither teachers nor researchers are always prepared. However, if participatory approaches are to succeed, the issue of trust has to be considered.

One aspect of the PLC framework that helps in trust development is the explicit positioning of the PLC facilitators as learners in the community effort, who do not have all the solutions from the beginning but who can contribute with their particular competences and knowledge, in the same way as teachers can and are expected to do. This standpoint is also possible in a PLC from the design research perspective, as researchers do not know in advance the findings they will meet or the solution of the problem they will investigate, neither they have a ready-made curriculum design to be used for such research. Researchers facilitating a PLC could make this situation explicit by sharing with teachers their need to learn from joint experience of what really works in practice, taking into account the fact that this implies to negotiate the distribution of expertise in ways that help the development of trust and self-confidence in the design team.

Importantly, the development of trust, above all, takes time. In research accounts it is often reported that the time needed to establish a professional culture receptive to peer feedback and critique is usually underestimated (Thomas et al. 1998). Time is critical for the development of teachers' empowerment and learning, which in turn facilitates trust development. In innovative projects with teachers some things can appear to be "changing" quickly: examples include the appearance of more collegiality or the use of the "innovation language". However, these are often superficial changes, as it is a lot easier to adopt the rhetoric of reform than to master its practices (Pintó 2005). The same happens in PLCs: the development of a real learning community has its own phases and rhythms. Research shows that PLCs *"demonstrate a developmental trajectory […] with regard to their capacity and disposition to dig deeply into matters of practice"* (Little 2002, p. 918). In general, an initial phase of "pseudo-community" is identified where conflict does not arise either because there is the perception of "convergence" or because there is not enough trust and self-confidence to comfortably express personal views (Grossman et al. 2000). Research provides no great help about how to overcome this phase. However, without enough time and concern for trust development, the stage of pseudo-community is unlikely to be overcome. The teacher-researcher partnership can be considered mature at the stage at which didactical and professional conflict can arise and be properly dealt with.

As a consequence, truly participatory approaches to curriculum design can only have a long-term view, in which their potential improves over time. Fortunately, the process of refinement in iterative cycles that is characteristic of design research fits adequately in this pattern and provides a good context for it to happen.

4.3 The Inquiry-Stance in Participatory Approaches to Curriculum Design

Within a PLC, inquiry becomes a central aspect of teachers' work (McLaughlin and Talbert 2001). The learning and inquiring culture where we situate our understanding of PLCs has a both evidence-based and research-based component. Participating in it implies seeking out and using relevant research results, and adopting more systematic approaches to the collection, analysis and use of evidence (Bolam et al. 2005). These are not easy tasks for teachers and targeted support is critical (Nelson 2009). Therefore both the research and evidence-based dimension of PLC justify the need for science education researchers' expertise within the community.

This approach to research and evidence in the PLC fits with a design research perspective on curriculum design and educational research, as in both of these a key element is the inquiry of practice to produce knowledge that is usable at both the local and global level.

There is, however, an interesting and subtle difference between the inquiry culture to be promoted in PLC and the research component of the design research perspective on curriculum design, which has to be negotiated. In PLCs it is generally agreed that the importance of teachers' inquiry relates to the process of participating and becoming capable members in such communities, that is, the importance of building a professional inquiring culture at teacher or school level where the search for solutions of local problems of practice is done in an informed and evidence-based way (Cochran-Smith and Lytle 2009; Nelson 2009). On the other hand, the design research paradigm is strongly theory oriented, stressing the importance of the contribution of this endeavour to research in the field (pieces of knowledge about science teaching and learning and design alternatives) and the design of innovative products (the final designed teaching learning sequence or environment) (Design-Based Research Collective 2003; Van den Akker et al. 2006). A truly participatory approach for design research inspired in the PLC concept will need to balance the process-product orientations of both perspectives. As a consequence, it should explicitly acknowledge and facilitate the contribution of the design research intervention to teacher and/or school development, classroom practice change and students' science learning, in addition to making a necessary contribution to the field of science education research.

This balance of purposes is not as difficult to reach in design research as it could seem. As McKenney and colleagues state (2006), both the aims of research and teacher professional development are compatible in the design research framework: "*When research methods are creatively and carefully designed, they can contribute to the tertiary output of design research [teacher professional development]. For example, data collection methods such as interviews, walkthroughs, discussions, observations and logbooks can be structured to stimulate dialogue, reflection or engagement among participants*". What the PCL framework can contribute to a design research intervention are examples of how to use these or other professional development tools to promote the *inquiry stance* that would allow, for instance, iterations of the designed curriculum materials with teachers understanding the reasons to iterate and without feeling disappointed for the changes made.

4.4 Impact on Teacher Learning and Students' Results of Participatory Approaches to Curriculum Design

Impact on students' learning is explicitly stated as the final goal of PLCs (Bolam et al. 2005). Behind this idea there is not only the naive assumption that good professional development produces superior teaching which increases student achievement (Supovitz and Turner 2000), but the concrete assumption that an explicit focus on inquiring the relationships between teaching and learning in a particular context will ensure the adequacy, mastery and return of this superior teaching (Blankstein et al. 2008; Little 2003; Nelson 2009; McLaughlin and Talbert 2006).

Initiatives within the PLC framework have been shown to make a significant difference in terms of directly measured student achievement (Bolam et al. 2005; McLaughlin and Talbert 2006; Stoll et al. 2006; Vescio et al. 2006). However, other authors report that the effects of PLCs in changing classroom practice are more mixed (Seashore et al. 2003). This is due to the fact that not any teacher community shares the characteristics of a PLC, such as an inquiry culture, that could promote teachers' change of practice (Grossman et al. 2000). In addition, even if change of practice is produced, we cannot simply equate it with improvement, assuming efficiency of any community of practice (Wenger 1998).

In this context, one could argue whether organising a PLC for orchestrating teachers' participation in a design research project will improve the local impact of the design and research effort. There are two main reasons to consider that it will. The first is the fact that in design research there has to be extensive and intensive collaboration with researchers. The second is related to the fact that curriculum design, a crucial task in design research, is a good context for teacher professional development.

Research on PLC shows the interesting relationship between teacher learning and teacher access to researchers' feedback and expertise (King and Newmann 2001). The external and research-informed view that researchers provide as facilitators, supporters and guiders of these communities is essential for them to be adequately fuelled, sustained and focused. Fortunately, in design research the presence of researchers in the design team is, as mentioned in previous paragraphs, intensive and long-term (McKenney et al. 2006). Researchers are not only part of the design team present in periodic meetings, but also present in the classroom when it is being implemented and after implementation, conducting debriefing sessions with the collaborating teachers (Gravemeijer and Cobb 2006). This extensive and intensive presence, if adequately articulated to pursue this aim, is expected to have an impact in teachers' professional development.

Regarding the task of participating in curriculum development, we have discussed in previous sections that participation in curriculum development is considered an effective teacher professional development activity, as there is evidence that active involvement of teachers in collaborative curriculum design helps them to change their beliefs, such as their perception of 'good teaching' and 'being a good teacher' (Voogt et al. 2011). From our viewpoint, within a participatory design research project the task of curriculum design becomes even more formative than in other collaborative curriculum design efforts. This is due to previously mentioned characteristics such as the continuous access to the expert view, the long-term orientation of the effort and the research and evidence-based perspective to curriculum design, among others. However, these characteristics would have an impact on teacher professional development only if happening in a trustworthy, learning and inquiry-oriented atmosphere that allows the teacher to exploit its full potential. As a consequence, despite it is inherent to participatory design research and has the potential to contribute to its tertiary output (teacher education), it is by doing so within a professional development framework (such as the PLC framework) that teachers' professional development could be ensured. This implies that creating, sustaining, fuelling and guiding a community of teachers also become an integral part of the design research experts' work.

4.5 Sustainability and Scalability of Participatory Curriculum Design: The Need to Focus on Teacher Leadership

The community framework is associated with sustainability, as PLCs have shown to enable the persistence and spreading of change (Ingvarson et al. 2005; Lerman and Zehetmeier 2008). Reasons are that, ideally, by promoting changes to the teachers' and school culture, PLCs should "survive" the initial project phase to continue on its own with minimal external input. However, sustainability cannot be taken for granted. Research shows that "breaking-the-mould" initiatives easily lose their momentum and experience an *"attrition of change"* (Fink 2000). As a consequence, authors raise the problem of how to achieve sustainable PLCs (Hargreaves 2007).

This need for sustainability of change processes does not belong uniquely to the PLC framework, and it is a general concern in science education, being also an issue within the design research approach. Fishman and colleagues have argued that most design research works do not explicitly address systemic issues such as sustainability, and that "*this limitation must be overcome if research is to create usable knowledge that addresses the challenges confronting innovations when implemented in real-world school contexts*" (p. 43, Fishman et al. 2004). As the authors point out, during most design research studies researchers establish a regular presence in the classroom to support the use of the innovation, sometimes modelling or co-leading instruction with the teacher (Cobb et al. 2003). This is done to establish conditions that are favourable to the innovation's success, which are necessary to study the phenomena of interest, and as previously mentioned, could have a positive impact on teachers' development. However, these conditions generally depend heavily upon the extra support from the researchers, which poses a challenge to the sustainability of the process. In our view, this is even more the case when teachers are invited to co-develop the innovation but this new role is not supported in order for them to achieve leadership and expertise as curriculum designers. Here, in addition to diminishing of the quality of the research outcomes, an opportunity for future impact is missed. Sustainability, if not exactly of the design research project, could be better achieved regarding its innovative *momentum* depending on how the participation with and among teachers is organised.

One way to promote sustainability within these participatory environments is to invest in building long-term capacity among teachers, by focusing on enhancing teacher leadership (Hargreaves and Fink 2006). Leadership is a well-known term in the literature (Little 2003) and has been studied within different frameworks, generally related to the individual agency of administrative leaders. However, this is not the sort of leadership that could be related to the sustainability of PLCs in participatory design research. Within these contexts, sustainability should be related with sustaining from the inside and in everyday practice the established culture of educational improvement. This view of leadership is of a more transformational nature: the ability to support and empower other teachers to increase students' and teachers' learning (Hargreaves and Fink 2006).

This task being so huge, scholars are drawing attention to frameworks that call for a more shared view of leadership. An emerging notion is that of "distributed leadership" (Spillane et al. 2001), a concept grounded in activity theory that focuses on the leadership practices of formal or informal teacher leaders. In an environment that values distributed leadership, knowledge, feedback and authority for decision making are shared among those who are most involved in enacting the innovation (Fishman et al. 2004).

The notion of distributed leadership described above fits interestingly with the idea of participatory approaches to curriculum design. This view of leadership allows distribution of empowerment and promotes a better use of teachers' knowledge and expertise, as, depending on the educational problem being dealt with by a PLC, different profiles of teacher leaders (those who will suit better its purpose) could emerge. Within a design research participatory approach, distributed leadership requires leadership to be distributed among researchers and teachers. This could create tensions particularly regarding the use of theory and the research agenda but will, in turn, contribute not only to the sustainability of the innovation but also to its quality, as richness of viewpoints and feasibility will be ensured (Reiser et al. 2000). In this sense, issues of leadership need to be specifically addressed if a participatory approach to curriculum design is undertaken. Problems of leadership such as the presence of negative leaders disempowering their colleagues or the lack of teacher leadership need to be brought to the foreground and dealt with.

If sustainability presents a challenge, scalability, another important measure of impact, is of greater concern for both the design research approach and the PLC framework. At the process level, both design research and PLC projects are purposefully and necessarily contextual and highly localised experiences. Due to their nature as high-effort and time-consuming scenarios, they are not easily scalable. In contexts where PLCs are being implemented following the political agenda in a quite technical, and thus superficial way, divergences regarding their original moral rationale and dilemmas regarding their usefulness and effectiveness in practice have recently appeared (Stoll and Louis 2007). In design research it is also mentioned that the need for an expansion of its research focuses towards the system-level (Fishman et al. 2004), despite the recognition of the enormous endeavour (and funding) that this change of level would imply (Burkhardt 2006).

At the product level, however, a certain scalability could be achieved and it is in fact considered one of the promising characteristics of design research which, "*in contrast to many types of conventional research, intrinsically confronts scalability issues*" (Dede 2005, p. 8). This refers to the possibility to transfer to other contexts both the knowledge and the curriculum designs obtained.

The possibility and limitations of transferring curriculum materials to teachers who have not participated in the design effort with the expectation that they would obtain similar gains than the participating teachers has been largely discussed in design research. These discussions can be situated in a spectrum from a focus on "teacher-proof materials" (Dede 2005) to the discussion on the structures that can make a particular curriculum design adaptable and somehow transferable in practice. Within this latter perspective, authors have proposed different alternatives such as modular structuring of the curriculum so that it offers different alternatives to teachers to choose (Ogborn 2010), the explicit identification and inclusion of teacher guidance regarding the instrumental aspects of the teaching activities and its implementation (Leach and Scott 2002), the framing of classroom activities and events as paradigm cases or prototypes to illuminate future practice (Gravemeijer and Cobb 2006) or the case of open TLSs with core and cloud elements, these latter ones to be re-designed by teachers (Besson et al. 2009, cited in Petros and Kariotiglou, chapter "Theoretical Issues Related to Designing and Developing Teaching-Learning Sequences", this volume), among others. All of them have in common to conceive the product of the participatory curriculum development effort *"as a template, or framework, to guide and influence teachers' actions in the classroom rather than as a blueprint to be enacted"* (Millar 2010, p. 55).

5 Tensions Between the Teacher's and Researcher's Agenda in a Participatory Approach to Design Research

The essential tension appearing in all participatory approaches is how to transcend teachers' knowledge and traditional practices in line with research results, while also having a participatory and highly "field-based" programme (Barab et al. 2002). In the literature on curriculum innovation this tension has been referred toas a tension between flexibility and fidelity: flexibility to be feasible, adapt to both teachers' rhythms and developmental level and accommodate local opportunities and constraints; fidelity to some basic core principles or theory of action to be in line with what we know from research. Researchers conceptualise and negotiate this tension rather differently. An interesting contribution is a "tight but loose" approach, described as strong adherence to few but central design principles (the tight part) with accommodations to the particularities of the context (the loose part) (Thompson and Wiliam 2005).

Within a participatory design research framework the "tight but loose" metaphor needs further development. In all design research studies flexibility regarding contextual constraints and needs is taken for granted, but a participatory approach will emphasise openness regarding the inclusion of teachers' expectations, knowledge and practices. The controversy is that in participatory design research the curriculum design has to be based on research results on X, but also it will be designed in collaboration with teachers who can be used to practices different than X, do not necessarily share the concern regarding X and have very likely not yet mastered what theory says about X. In this context, different strategies addressed to negotiate the flexibility-fidelity tension could help: a willingness to agree what is the problem to address; a constructive analysis of the successes and limitations of current practice; a critical discussion of the diversity of theoretical possibilities of action and their known impacts; an openness to transform theoretical design principles into feasible ones, etc. The different ways to realise these strategies involve "how tight needs the tight part to be", which depends on the nature of the research problem, the view, values and expectations of participants regarding research and practice and the contextual characteristics of the participatory curriculum design effort. No cookbook recipes can be provided. However, our argument is that when participatory design research is orchestrated in line with ideas from the community framework, the culture of learning and inquiry as stance within a trustful atmosphere, the provision of time and support, and the distribution of leadership will facilitate the use of strategies to negotiate the flexibility-fidelity dilemma in a truly participatory and knowledgeable way. As DBR researchers have already discussed, to find the middle ground between researchers and teachers "*requires sophistication and patience; yet this is the current climate within which DBR must now function*" (Dede 2005, p.8).

In the contexts described, an important tension that researchers are confronted with is how to combine both the different roles they are playing and the different purposes they are pursuing: on the one hand, as researcher within a design research approach; on the other, as facilitator of the PLC doing this. It is clear that these different roles and tasks require different kinds of expertise and cannot be played with the same intensity in every context for every study. Decisions regarding what aspects of the organisation of the participation will be prioritised need to be made. In doing so, researchers have to consider the scope of change of their particular design research study. When the curriculum design presents a great challenge (when the practices to be changed *"are recurrent, central, and entrenched within school culture"*), investing in forming a professional community, rather than an extra task, becomes a necessity *"to counteract the force of old habit"* (Thompson and Wiliam 2005).

6 Summary and Conclusions

As discussed in previous chapters, design research in different forms (such as DBR and TLSs research) is in the ascendant for scholars as an approach that not only contributes to research, but aims to directly influence practice from an analysis of actual teaching and learning problems and the production of high-quality teaching and learning materials (Psillos and Kariotoglou, chapter "Theoretical Issues Related to Designing and Developing Teaching-Learning Sequences", this volume). The argument throughout this paper is that this already attractive approach can be enriched with a more sophisticated participatory construct for guiding the organisation of the collaboration with practitioners it entails.

In this sense, powerful and well-known notions from the fields of educational reform and professional development, such as the community framework, have been used to illuminate how to increase the effectiveness of the design research efforts. By reviewing the theoretical underpinnings, empirical results and challenges associated with well-known notions such as PLCs, the importance of the design team and how it is guided and sustained becomes an essential and crucial part of the researchers' agenda. Different ways of organising it lead to differences in teachers' participation, the quality of teachers' development and thus in their ownership of the innovation, which are crucial for an adequate implementation in a highly demanding context where consideration of design principles and refinement of teaching and learning materials is pursued. Greater effort is required if a certain sustainability of the innovative *momentum* is to be achieved. As a consequence, this paper argues that the design of the participatory situation is neither a minor, nor just an organisational task, for any design research effort undertaken in collaboration with teachers.

One could argue that, within a complex scenario such as the one set within the design research approach, it is not feasible to place the same importance on the organisation of the participatory situation (even less on its study) as on theoretical contributions on design principles or evidence-based curriculum designs. We consider, however, that making an explicit effort to enrich the way in which the necessary collaboration with teachers is organised increases the quality and validity of both the research results and its products. In addition, by understanding this context as one with potential for the development of the teachers involved and the emergence of teacher or school-based communities that can achieve certain sustainability, a genuine contribution to future research and practice is made. This signals a new area where more research is needed: that of teachers' development and community formation within design research scenarios.

A necessary remark will be to clarify that in this paper it is not suggested that all science curricular innovation neither all science education research should be done as a participatory design research. In such a scenario, concerns regarding cost-effectiveness and scalability will reasonably emerge, together with a discussion on the crucial role of "normal" vs design research (Sloane 2006). For instance, exemplary curriculum materials developed by researchers alone or in collaboration with expert teachers, such as those designed in most TLS research, are needed in science education. Research relates studying and adapting exemplary materials to teachers' effectiveness in realising change, as concrete artefacts that support reflection and enactment (Voogt et al. 2011). In this sense, our claim is modest and refers to research that wants to deal with the "dilemmas of practice", as most design research does. For this type of research, the organisation of a participatory approach according to what we know from the community framework is feasible and can substantially improve effectiveness, quality and sustainability.

Finally, we are just starting to explore the power of the idea of participation, not only referred to personal collaboration but as a characteristic trend of the science education culture that permeates products, processes and values. Interesting contributions in this direction are recent reflections about how a more democratic way of framing science education standards, using non-authoritarian and participatory language, could transform science teaching and learning (Wallace 2012). This chapter wants to contribute to this line of thought and action, by emphasising the power of orchestrating these participatory efforts according to current knowledge.

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Part II
Aspects of Materials Science and Their Educational Adaptation

Materials Science: Trends, Material Properties and Educational Perspectives

Euripides Hatzikraniotis and Theodora Kyratsi

1 Introduction: Terms and Terminology in Materials Science

The discipline of *Materials Science* (MS) involves the investigation of the relationships that exist between the structure and properties of materials. On the other hand, *Materials Engineering* deals, on the basis of these structure–property correlations, with the design or engineering of the structure of a material to produce a predetermined set of properties (Callister 2006).

Overall, Materials Science and Engineering (MSE) is an interdisciplinary field which deals in inventing new materials and/or improving previously known materials by developing a deeper understanding of the microstructure – composition – synthesis – processing relationships. The term *composition* refers to the chemical make-up of a material. The term *structure* refers to a description of the arrangements of atoms or ions in a material. Materials scientists not only deal with the development of the materials, but also with the synthesis, processing and manufacturing processes related to the production components. The term *synthesis* refers to how materials are made (from naturally occurring or other chemicals). The term *processing* refers to how materials are shaped into useful components or their properties are changed (Askeland and Fulay 2006). Figure 1 shows how the composition (e.g., iron-based material, aluminum-based or other), the synthesis and processing (e.g., growth from melt, powder metallurgy processes, etc) and the structure (at atomic and microscopic level) interact, resulting in specific properties, thus in certain performance of the materials.

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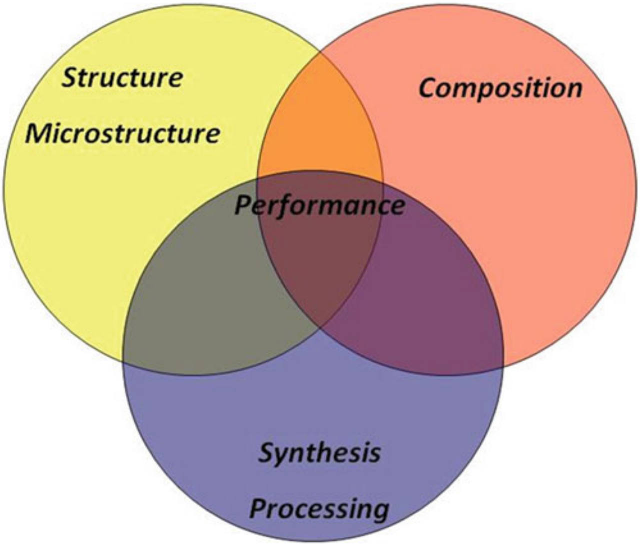

Fig. 1 Materials science and engineering content

An applied scientist or engineer, whether mechanical, civil, chemical, or electrical, will in some way be exposed to a design problem involving materials. Examples might include a transmission gear, the superstructure for a building, food packaging, or an integrated circuit chip. Materials scientists and engineers are specialists on the investigation and the design of materials (Callister 2006).

Solid materials have been conveniently grouped into three basic classifications (Callister 2006):

- Metals and Alloys
- Ceramics, Glasses, and Glass-ceramics
- Polymers (plastics), Thermoplastics, and Thermosets

This scheme is based primarily on chemical makeup and atomic structure, and most materials fall into one distinct grouping or another, although there are some intermediates. Therefore, there are other groups of important engineering materials (Askeland and Fulay 2006):

- Composites, that consist of combinations of two or more different materials
- Semiconductors, that are utilized because of their unusual electrical characteristics
- Biomaterials, that are implanted into the human body
- Advanced materials, Smart materials, Nano-materials

Materials that are utilized in high-technology (or high-tech) applications are sometimes termed *advanced materials*. By high technology we mean a device or product that operates or functions using relatively complex and sophisticated principles; examples include electronic equipment, computers, fiber-optic systems, spacecraft, aircraft, and military rocketry. These advanced materials are typically either traditional materials, whose properties have been enhanced, or newly developed high-performance materials. Furthermore, they may be of all material types (e.g., metals, ceramics, polymers), and are normally relatively expensive (Callister 2006).

Smart or intelligent materials are new and state-of-the art materials with a dramatical influence on many of our technologies. The term "smart" implies that these materials are able to sense changes in their environments and then respond to these changes in predetermined manners. Examples of such materials are the shape memory alloys, piezoelectric ceramics, and magnetostrictive materials (Kakani and Kakani 2008).

Nanostructured materials are those materials whose structural elements have dimensions in the range of 1–100 nm. These small groups of atoms, in general, go by different names such as nanoparticles, nanocrystals, and quantum dots. On 18 October 2011, the European Commission adopted the Recommendation on the definition of a nanomaterial. According to this Recommendation a "Nanomaterial" means: *A natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50 % or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm – 100 nm* (Europa 2011).

Significant work is being carried out on nanostructured materials from the past decade since they were found to have potential for high technology engineering applications. Remarkable variations in fundamental electrical, optical, and magnetic properties occur as we go from an 'infinitely extended' solid to a particle consisting of a countable number of atoms. Today, nanotechnology is considered to be the next enabling technology that will redesign the future of several technologies, products and markets (Kakani and Kakani 2008).

This chapter consists of two parts:

- Part A concerns Materials Science as an interdisciplinary scientific field presenting a short history of materials and then discussing material properties.
- Part B concerns some educational aspects in Materials Science, both at university as well as at pre-university level.

It is quite a challenge to write a technical paper addressed to non-technical audience. Not only a deep understanding is required, but also the language and terminology should be understandable from non-technical audience. In addition, the limited space of a paper (as opposite to a book) makes it even more difficult to address the topics in some reasonable detail, with examples. Two classical text-books have been selected as reference, Askeland and Fulay (2006) and Callister (2006). The first part of this chapter may therefore serve as a reference for further reading.

2 Part A

Part A includes a short history of materials and the field of MS. Moreover, the aim is to introduce the reader to basic terms of MS, as an interdisciplinary field including fundamentals of chemistry and physics. The materials structure, at atomic and microscopic level, is included. The importance of materials synthesis is referred in terms of structural and morphological aspects. Then, an introduction to the material properties, such as thermal, electrical, optical, magnetic, etc is included and finally some comments are made on the connection between properties and structural aspects.

2.1 History of Materials and Materials Science

Mankind and materials are strongly connected from the first beginning. Man first used stone, wood, bones, fibers, animal skin, clays, and within the next centuries and thousands of years he developed more and more sophisticated ways and materials to serve specific purposes.

The History of the Materials includes certain ancient periods based on the kind of materials that was mainly used and/or developed (Hummel 2004):

- The Stone Age (which began about 2.5 million years ago) was divided into the Paleolithic, the Mesolithic and the Neolithic periods.
- The Copper–Stone Age (or Chalcolithic Period) that actually expresses the coexistence of the stone and the copper ages. It is believed that the Neolithic man started using copper at about 8000 BC. Chalcolithic man realized the advantages of the copper, such as elasticity and mainly plasticity that gave him the chance to easily make various shapes, in comparison to stones. However, as copper is a relatively soft material and could not be used as a weapon or tool, bronze had been discovered to fulfill this gap.
- The Bronze Age (3000–1000 BC). By experimentation or by chance, the Chalcolithic man had found that he can make alloys (a material that consist of more than one metals) with improved properties. Bronze, an alloy of copper and tin, has higher hardness compared to copper and can be handled at lower temperatures. Copper–arsenic alloys were firstly used and then later the copper–tin alloys were discovered. The latter actually substituted the copper–arsenic alloys because they were stronger and easier to cast.
- The Iron Age (began between 1500 and 1000 BC). It is the last one based on the three-age system in archaeology. It seems that iron was used thousands of years before the so-called Iron Age (iron–nickel alloys), but the supply of such alloys was limited. In addition, iron by itself is not a useful material for tools, unless it is combined with carbon and steels are produced (iron with carbon of 0.3–1.2 wt %). Steel tools are much stronger than bronze and are obviously preferable. However, it was difficult to produce steel and it seems that this was one of the main reasons for the delay of the beginning of Iron Age.
- The Age of Electronic Materials (1950-today). Continuing the classification based on the materials that had the greatest impact and taking into account that electricity caused a major change, the Age of Electronic materials had started. Conductors, insulators, semiconductors, magnetic, optical materials are all materials whose properties are related to phenomena where electrons participate.

All the above periods are defined based on findings of archeologists and scholars related to weapons, tools and art. Besides these periods, one cannot exclude "The Ceramic Age" and "The Age of Organic Materials." These eras cover basically all the period that human life exists and this is the reason that they do not appear in the abovementioned history review.

- The Ceramic Age. Materials such as stones, minerals, clays, quartz, etc are continuously used by man since the beginning of his existence. Clays were extensively used from early times because it is widely available material, it is pliable when mixed with water, it becomes hard when dried, generally stable at higher temperatures, etc. Glasses come much later due to the high melting point of sand (silica) that gives the glass (the oldest glass objects were dated back to about 2500 BC). Concretes are composite materials that consist of two ceramic phases. The ancient Romans and Greeks already used such materials. Advanced ceramics are manufactured from pure oxides, nitrides, carbides and/or borides.
- The Age of Organic Materials. Natural fibers seem to be the first material that was used even by animals (webs made by spiders, nests by mammals, etc). The first material that probably man used to make fabric was wool. Cotton, silk, animal fibers came later. Wood was always a major material in everyday life. Polymers (natural and synthetic) mainly consist of hydrocarbons. Also other elements such as nitrogen, oxygen, chlorine, etc can be involved. Depending on the type of their monomer, their chains, their architecture, etc, they can cover an extremely wide range of properties of materials.

Based on the above review it is obvious that ancient man had knowledge and technology in the field of Materials Science and Engineering (MSE). Then, until even up to modern period, all knowledge and technology was coming from experience and was not really connected to what we call today MSE (the relationship between the structure of materials at atomic or molecular scales as well as their microstructure and their macroscopic properties). Actually, the major breakthrough in the understanding of materials came from the American scientist Josiah Willard Gibbs in the nineteenth century who demonstrated that the thermodynamic properties related to atomic structure in various phases are related to the physical properties of a material.

2.2 Material Structure and Properties

The list of different properties of the materials is long and is impossible to be discussed in this chapter. A whole book is needed to introduce the basic principles of the properties (or attributes) of the materials. Several of them, like density (mass per unit volume) are familiar enough, but others are not. Studying the materials can be categorized into three different groups: at (a) Atomic level (atomic structure), (b) Microscopic level (microstructure) and (c) Macroscopic level (physical and other properties). In this part a brief introduction to the classification of the material properties is aimed.

2.2.1 Material Structure

At Atomic Level By the term "crystal structure" we mean a unique arrangement of atoms or molecules in a crystalline liquid or solid, to form a lattice and we refer to this as "atomic level." A crystal structure is composed of a pattern, a set of atoms arranged in a particular way, and a lattice exhibiting long-range order and symmetry. Lattice systems are a grouping of crystal structures according to the axial system used. There are seven lattice systems and six crystal families ranging from simple (high symmetry) to more complex (low symmetry). The six crystal families are cubic, hexagonal, tetragonal, rhombohedral, orthorhombic, monoclinic and triclinic. In fact, material properties largely depend on the crystal structure, and the local coordination of atoms.

The crystal structure is of major importance and actually defines the material properties; thus, its study is necessary in the Materials Science and Engineering field. A common example concerns carbon. Carbon can be found in different forms, from the crystal structure point of view. A common form is graphite where the carbon atoms are connected to each other via strong covalent bonds and form layers. The layers are connected to each other via weak Van der Waals bonds as shown in Fig. 2. On the other hand, another form of carbon is the well-known diamond that is a more compact structure as shown in Fig. 2.

Graphite properties are completely different from those of diamond due to their different crystal structure, even though they are both carbon. The graphite structure is layered and the layers are weakly bounded to each other, thus easily cleaved. This makes the material useful as lubricant or pencils. On the other hand, the diamond is a strong, three-dimensional structure that results in high-hardness, strength, durability.

The most common way to determine a material's structure, i.e., the determination of the unit cell, is through X-Ray Diffraction experiments (XRD). When X-rays pass through a crystalline material, they diffract following the Bragg's law, $2d \cdot \sin\theta = \lambda$, where d is the d-spacing of the crystallographic planes, θ is the Bragg angle where the diffraction occurs and λ is the used wavelength (Cullity and Stock 2001). When material is in powder form, with many crystallites in random directions, Bragg diffraction may occur from all possible crystallographic planes, resulting in an XRD pattern (Fig. 3). XRD pattern consists of a series of peaks versus the incident angle (2θ). The position of the observed peaks is characteristic of the crystal structure and the lattice constant of material under examination. Indexing (hkl) of different peaks[1] is done through selection rules depending on the symmetry of the unit cell and is routinely used on the characterization of the crystalline materials. The importance of this technique is based on the existence of a unique pattern for each compound (fingerprint).

[1] Miller indices (*h*, *k*, *l*) form a notation system in crystallography for planes in crystal lattices. Each index denotes a plane orthogonal to a direction (h, k, l) in the basis of the reciprocal lattice vectors.

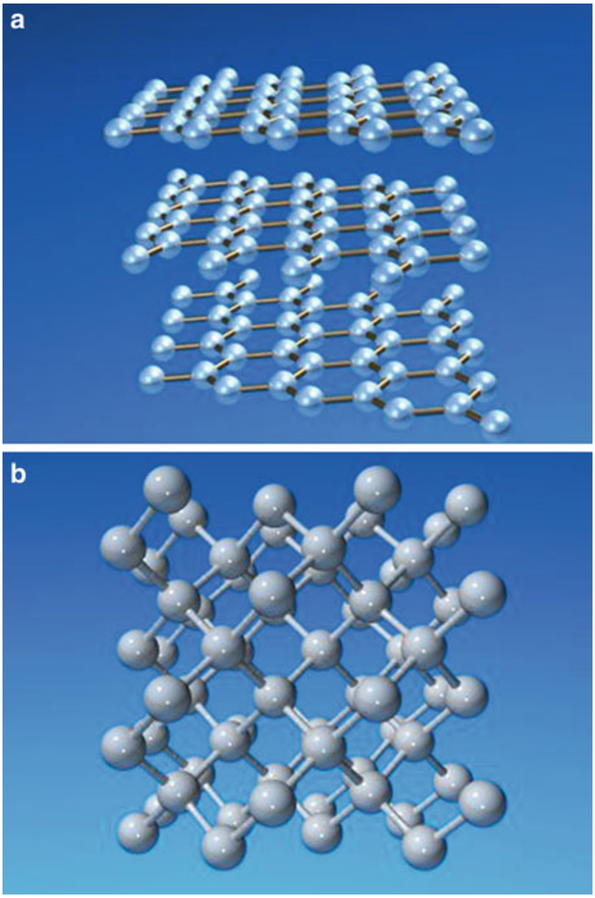

Fig. 2 Crystal structure of (**a**) graphite and (**b**) diamond consisting of carbon atoms (After www.webelements.com)

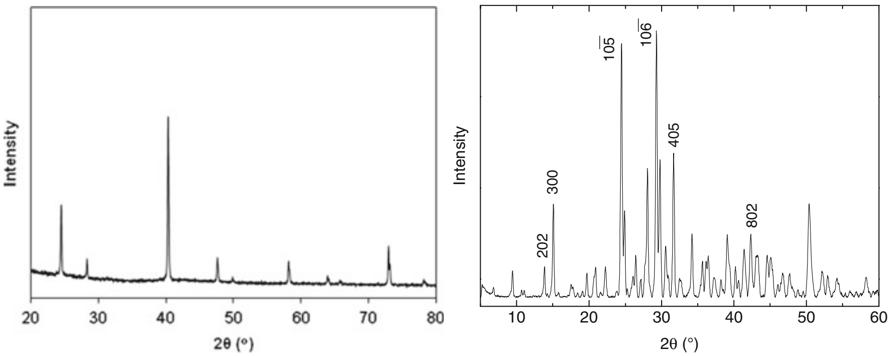

Fig. 3 XRD pattern for Mg_2Si, a cubic structure (*left*) (Ioannou et al 2012) and $K_2Bi_8Se_{13}$, a more complex (monoclinic) structure (*right*) (Chung et al. 1997)

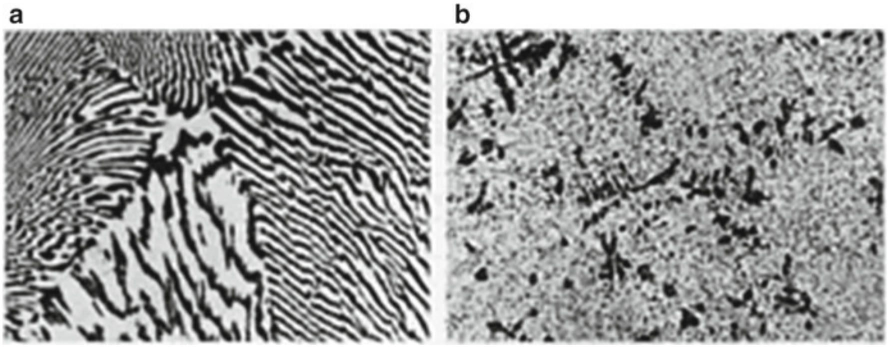

Fig. 4 The microstructure of 63 % Sn–37 % Pb alloy. (**a**) Slowly cooled sample shows a lamellar structure consisting of dark platelets of lead-rich solid solution and light platelets of tin. (**b**) More rapidly cooled sample shows globules of lead-rich solid solution, some of which exhibit a slightly dendritic structure, in a matrix of tin. http://www1.asminternational.org/asmenterprise/apd/help/intro.aspx

At Microscopic Level The microstructure of a material is actually related to the way the different phases (regions with the same atomic structure, chemical and physical properties) co-exist. For example, Pb-Sn system concerns one of the most commonly used solder in joining materials and serves as electrical connector in circuit boards. The microstructure of the material consists of alternating layers of a Pb-rich-phase solid solution (dark layers), and a Sn-rich-phase solid solution (light layers) depending on the cooling conditions after melting, see Fig. 4.

The structure of the products mainly at microscopic level strongly depends on the way they are made. The materials synthesis is a major part of Materials Science and Engineering and the existing phase diagrams are very helpful to predict the microstructure of the products. The phase diagrams represent the relationships between temperature, the pressure, the compositions and the quantities of phases at equilibrium (Callister 2006). The phase diagram of the eutectic Sn-Pb system is shown in Fig. 5.

Optical and electron microscopes are common tools for the study of the morphology of the materials at microscopic level. Electron Microscopy has expanded the characterization capabilities from 1 μm down to 1 Å (10^{-10} m).

At Macroscopic Level The macroscopic level refers to material properties such as mechanical, thermal, electrical, optical, etc that will be presented below.

2.2.2 Material Properties

2.2.2.1 Materials Composition and Density

Density is a material property related to composition and crystal structure. Theoretical density of a material is calculated by counting the atoms (atomic mass) per unit cell, and dividing by unit cell volume. In real bulk materials density is

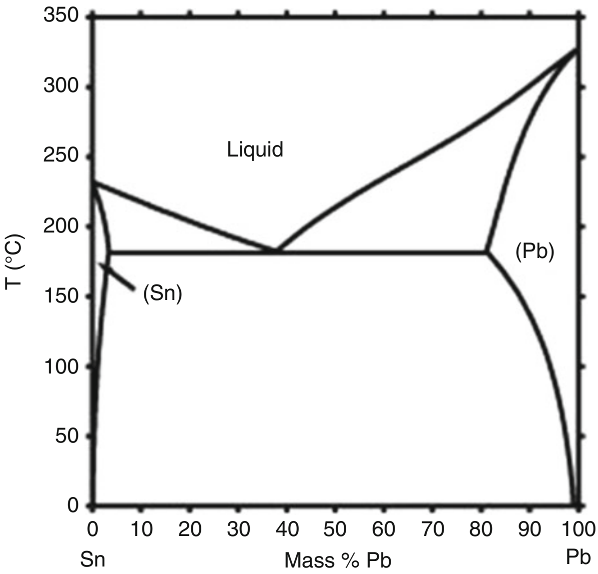

Fig. 5 Phase diagrams of Pb-Sn system (http://www.metallurgy.nist.gov/phase/solder/pbsn.html)

usually measured by Archimedes' principle. Density is found dependent on the atomic number for a pure element: going down one column in the periodic table, density increases (Fig. 6). In compounds, density in general decreases, from metals and alloys to ceramics, to polymers and to composites or fibers. Furthermore, crystalline materials have higher density than their amorphous counterparts.

To determine the chemical composition of a material, various techniques, such as Electron Dispersion Spectroscopy (EDS), X-Ray Fluorescence (XRF) or Inductively Coupled Plasma Mass Spectrometry (ICP-MS), are commonly used.

2.2.2.2 Mechanical Properties

The *Elastic Modulus* reflects the material's resistance to elastic deformation. Most structures are designed to ensure that only elastic deformation will result when a stress is applied. This means that when the applied load is released, the piece returns to its original shape and it is highly desirable. Therefore, is required to know the stress level at which plastic deformation starts (mainly permanent deformation), which is called *yield strength* or *yield point*. *Ductility*, another important mechanical property, is a measure of the degree of plastic deformation that has been sustained at fracture. A material that experiences much plastic deformation is called ductile and on the other hand, the one that shows very little plastic deformation upon fracture is called brittle.

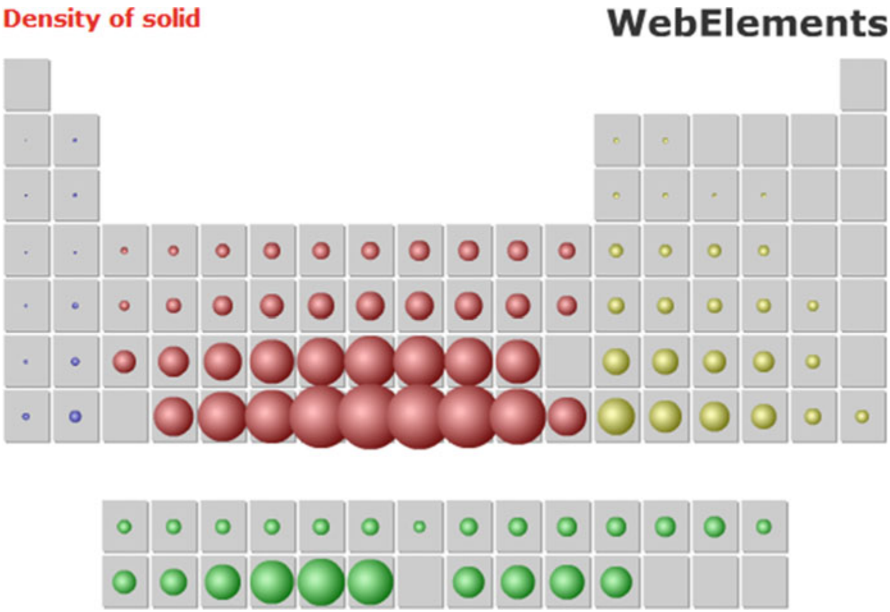

Fig. 6 Density of the elements as a function of their position in the periodic Table. The larger the sphere, the larger the density (After www.webelements.com)

2.2.2.3 Thermal Properties

The properties of a material change with temperature, i.e its strength falls, it may oxidize, degrade or decompose. Therefore, it is important to define the maximum service temperature, as limiting temperature. Above this temperature the use of the material is impractical. Most polymers have relatively low service temperature in contrast with ceramics that present high values. In addition, the fact that the materials expand with the increase of temperatures is related to the change in length for a specific temperature change.

The transport of thermal energy from high- to low-temperature regions of a material is called thermal conduction. Materials with high thermal conductivity (i.e., metals) are used in cooking pans, heat exchangers, whereas low thermal conductivity materials, such as bricks, are used for insulation. Thermal conductivity (κ) in bulk materials has two contributions, $\kappa = \kappa_E + \kappa_L$, the electronic part ($\kappa_E$) and the lattice contribution (κ_L). In metals the electronic part is far more significant, in ceramics the lattice is more dominant.

Another thermal quantity is "heat capacity". Heat capacity represents the quantity of heat required to produce a unit rise in temperature for one mole of a substance, and is important in comparing different materials regardless the time required for the rise in temperature.

2.2.2.4 Electrical, Magnetic and Optical Properties

Electrical conductivity reflects the ability of a material to conduct electrical current that is a key property which enables the generation of light, power, control and communication. Solid materials are grouped into three basic classifications according to this property: *conductors, semiconductors* and *insulators.*

Certain materials (ferromagnets) possess a permanent *magnetic moment* in the absence of an external field, and manifest very large and permanent magnetizations and are used in headphones, motors and dynamos. On the other hand, diamagnetic and paramagnetic materials exhibit magnetization only in the presence of an external field.

Another classification of materials is based on their ability to let the light transmit through them: these are transparent (light is transmitted), opaque (light is reflected) and translucent (light is transmitted diffusely). Furthermore, the ability of a material to allow the passage of electromagnetic radiation is related to its *dielectric constant*. Materials with high *dielectric constant* respond to an electric field by shifting their electrons about; those with low *dielectric constant* do not respond.

When light is transmitted through the materials, with relatively little absorption and reflection, they are then transparent. When the materials reflect the light, they are opaque, and when light is transmitted diffusely, they are translucent. Furthermore, the ability of a material to allow the passage of electromagnetic radiation or to reflect it is related to its *dielectric constant*.

2.2.3 Structure and Properties

In general, there is a strong connection between structure and properties. Selected examples are included in this chapter since a detailed presentation cannot be limited in few pages. Perhaps the most characteristic example on how structure may affect properties is the case of graphite and diamond. Diamond's chemical composition and crystal structure make it a very unique member of the mineral kingdom. Diamond is the only gem known made of a single element: carbon. It is an allotropic form[2] of carbon, others are, spherical or cylindrical fullerenes (nanotubes and buckyballs), glassy and amorphous carbon, carbon foams, etc.

Diamond (as opposed to graphite) has a 3D tetrahedral structure (see Fig. 2) which is stabilized by resonance of the bonding electrons among adjacent bonds of sp^3 bond hybridization,[3] while graphite has a planar structure of sp^2 bonds. This particular structure makes diamond a wide gap semiconductor while graphite is

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[2] Allotropes are different structural forms of the same element and can exhibit quite different physical properties and chemical behavior. Many compound materials exhibit *"polymorphism"*; they can exist in different structures having the same chemical compositions, are called polymorphs.

[3] Hybridization is the concept of mixing atomic orbitals into new (hybrid) orbitals with different energies, shapes, etc., suitable for the pairing of electrons to form chemical bonds. Hybrid orbitals are very useful in the explanation of molecular geometry and atomic bonding properties.

zero-gap. However, not all other materials that have the same tetrahedral structure (so called “diamond structure”) are precious stones. Examples are Ge and Si. What makes diamond unique are the high surface energy and the exceptionally high ratios of its shear moduli to its bulk modulus (which makes deformation very difficult). Because of its unique strength diamond can perform exceptionally in mechanical devices such as: pressure vessels, ultracentrifuges, springs, flywheels, and cutting (or drawing) tools.

Until now, all carbon structures have been classified either as crystalline – built from repeating atomic units – or as amorphous, that is, lacking the long-range structural order seen in crystals. Recently, *ordered amorphous carbon clusters* have been synthesized, the first hybridized carbon structure, that is part amorphous and part crystalline. This new form of carbon is hard enough to indent even diamond (Wang et al 2012).

Materials scientists and engineers, over last 40–50 years, have produced many new materials with desirable properties. Taking the example of carbon, Materials Scientists have managed to roll-over a graphite layer to produce a carbon-nanotube or to wrap up a distorted graphite layer to produce a spherical fullerene, also called buckyball as it resembles much the football ball. A common method used to produce fullerenes is to send a large current between two nearby graphite electrodes in an inert atmosphere. For the past two decades, the chemical and physical properties of fullerenes have been a hot topic in the field of research and development. Metallofullerene-based inoculates using the rhonditic steel process are beginning production as one of the first commercially-viable uses of buckyballs. Rhondite is a nanoscale helical carbon-based structure created by Robert Job that may be used in the production of steels and alloys to increase hardness, strength, ductility and wear resistance.

Allotropes (like diamond and graphite) are different structural modifications of an element; the atoms of the element are bonded together in a different manner. An example of allotropes having different chemical behavior is oxygen, which appears in two forms; ozone (O_3) is a much stronger oxidizing agent than dioxygen (O_2). The change between allotropic forms is triggered by the same forces that affect other structures, i.e., pressure, light and temperature. For instance, iron changes from a body-centered cubic structure (ferrite) to a face-centered cubic structure (austenite) above 906 °C, and tin undergoes a transformation known as tin-pest from a metallic form to a semiconductor form below 13.2 °C.

Different polymorphs of the same crystals have the same chemical compositions and similar chemical properties, but their physical properties such as density, specific heat, conductivity, melting point, and optical behavior depend on the arrangement of the atoms in the structure. Some examples are $CaCO_3$, ZnS, and HgI_2. $CaCO_3$ exists in two forms: (1) calcite, which is rhombohedral, uniaxial and has a density of 2.71 g/cm^3; (2) argonite, which is orthorhombic, biaxial, and has a density of 2.94 g/cm^3. ZnS exists in two forms: (1) wurtzite, which is hexagonal, and (2) sphalerite, which is cubic (diamond type). HgI_2 also exists in two forms: (1) red in color and having tetragonal structure and (2) yellow in color and having orthorhombic structure.

Silicon carbide is a compound of silicon and carbon with chemical formula SiC. It is unique in regard that as more as 250 polymorphs of silicon carbide had been identified by 2006. The different polymorphs (or polytypes) have widely ranging physical properties. The so-called "3C-SiC"[4] has the highest electron mobility and saturation velocity due to the reduced phonon scattering resulting from the higher symmetry. Depending on the way the atoms are bonded, the band gaps differ widely among the polytypes ranging from 2.36 eV for 3C-SiC to 3.23 eV for 4H-SiC to 3.05 eV for 6H-SiC. Thermal conductivity and bulk modulus are also different in the three polytypes (3.6 W/m.K for 3C-SiC, 3.7 W/m.K for 4H-SiC, 4.9 W/m.K for 6H-SiC and 250 GPa for the cubic, 220 GPa for the hexagonal).

Another example on how structure and processing may affect material properties in a desirable way is the case of producing low thermal conductivity materials. It is known that when a material (AB) is *alloyed* with some other material (AC) to form $AB_{1-X}C_X$, the resulting *solid solution* has in general (for composition $x \sim 0.5$) a lower thermal conductivity, with respect to the initial materials. Processing materials with low thermal conductivity may reduce further their thermal conduction. Porous materials (for example) have lower thermal conductivity than bulk counterparts. An extensive network of porous media may be the solution for low-thermal conductivity materials. Aerogel (Fig. 9) is a synthetic porous ultralight material derived from a gel. The result is a solid with extremely low density and thermal conductivity. Despite their name, aero-gels are rigid solid materials. They have very high porosity (over 50 %) and specific surface area ranging between 400 and 1000 m^2/g. Aerogels are good thermal insulators because of their porous structure and they almost nullify heat transfer (Wikipedia site).

In many cases, the search of a new material with desirable properties may seem straightforward. For example, carbon fibers may be used to produce tennis rackets which will have the desirable flexibility and lightness. Ceramic Aero-gel is a solution when a light material is needed for thermal shielding applications [Wikipedia site]. However, in other cases the technological demand may consist of two property trends contradicting each other; an example of such contradicting property trends is "thermal conductivity of a material should be kept low, and, at the same time, material has to be a good electron conductor". This seems much of a challenge for materials science, as good electrical conductors (e.g., metals) are known to have high thermal conductivity as well. One of the promising ways to address this problem is the development of new inhomogeneous materials including nanostructuring (Chung 2000). Phonons will scatter on nanoinclusion boundaries and therefore reduce the thermal conductivity. For adequate high electrical conductivity one should look for heavily doped semiconductors, where a dopant is used to tune the carrier concentration. However, if dopants are distributed all over the bulk material, carrier mobility will be reduced due to a notable ionized impurity electron scatter-

[4] The most common SiC polytypes are the "3C", "4H" and "6H". The letter "C" refers to cubic the letter "H" to hexagonal. Lattice constant is 4.36 Å for the cubic polytype, while for the hexagonal ones, the in plane lattice constant is 3.07 Å, and they differ in the c-axis (10.05 Å for 4H and 15.11 Å for 6H).

ing. The solution to this problem is the "doping modulation". Modulation doped materials are two-phase composites with a matrix-phase of low carrier concentration and heavily doped inclusions used to provide the carriers (Zebarjadi et al. 2012).

Nanostructuring and nano-materials are the current trends in materials science. What makes nano-materials so different and so intriguing? Their extremely small feature size is of the same scale as the critical size for physical phenomena, surfaces and interfaces are also important in explaining nano-material behavior. In bulk materials, only a relatively small percentage of atoms will be at or near a surface or interface (like a crystal grain boundary). In nano-materials, the small feature size ensures that many atoms, perhaps half or more in some cases, will be near interfaces. Surface properties such as energy levels, electronic structure, and reactivity can be quite different from interior states, and give rise to quite different material properties. In the nano-particles with some of its dimensions smaller than 10 nm, new effects from the time of laws of classical physics are no longer valid and we need quantum physics to explain them. For example, the minimum potential energy of an electron confined in a nano-particle is higher than expected in classical physics and energy levels of different electronic states are discrete. Due to quantum confinement, the particle size has a drastic effect on the density of electronic states and thus on the optical response.

The above are just a few, out of numerous examples one may find in the connection structure-to-properties and the properties-to-processing relation. In spite of the tremendous progress that has been made in the discipline of materials science over the past years, there still remain technological challenges, including the development of even more sophisticated and specialized materials, as well as consideration of the environmental impact of materials production.

3 Part B

Why one studies materials? Materials are probably more deep-seated in our culture than most of us realize. Transportation, housing, clothing, communication, recreation, and food production, i.e., virtually every segment of our everyday lives is influenced more or less by materials. Historically, the development and advancement of societies have been intimately tied to the members' ability to produce and manipulate materials to fulfill their needs. In fact, early civilizations have been designated by the level of their materials' development.

As stated earlier, the discipline of materials science involves investigating the relationships that exist between the structures and properties of materials. Materials scientists and engineers are specialists who are totally involved in the investigation and design of materials. The more familiar a scientist is with various characteristics and structure–property relationships, as well as processing techniques of materials, the more proficient and confident he will be in making judicious materials choices. In this part we shall briefly examine the educational aspects of Materials Science.

3.1 *Education in Materials Science*

The necessity of education in Materials Science is widely recognized. In the beginning of the twentieth century, most engineering schools had a department of metallurgy and perhaps of ceramics as well[5]. In the post-World-War-II era, the systematic study of polymers advanced particularly rapidly. Later, materials science started to be considered as a new interdisciplinary field in its own right and, finally, Northwestern University instituted the first Materials Science Department in 1955.

Materials Research Society (MRS), officially founded in 1973, is an organization of materials researchers from academia, industry, and government that promotes communication for the advancement of interdisciplinary materials research to improve the quality of life. The Society's core principles were interdisciplinarity, focused symposia, and greater interaction among researchers. As of 2012, MRS has grown to nearly 16,000 members from the United States and over 80 other countries. The Society sponsors two major international annual Meetings encompassing approximately 100 topical symposia, offering symposium tutorials and networking opportunities, and also sponsors numerous single-topic scientific meetings (MRS site 2012).

Since 2000, there is a symposium devoted to Materials Science and Education in MRS meetings, there exists the International Council on Materials Education, continuing agency of the Materials Science and Engineering Community worldwide, a peer review journal is published (Journal of Materials Education, since 1979) and numerous attempts in various University sites, to introduce Materials Science and Technology to high-school or to general public. In this part we will discuss the structure of education in Materials Science, at formal education (pre- and university level); attempt to introduce Materials Science in high school education in informal (out-curricula) level; and finally conclude with some available educational resources.

3.1.1 Formal Education

At professional and graduate level there are two approaches to Materials Science and Engineering, as depicted in Fig. 7: science-driven and design-driven approaches.

In a *science-driven* approach, one usually starts from the atoms and crystal structure, to the interfaces and defect structure, to the composition and micro-structure, to end up with material properties, and finally to the end product. This is a typical approach to curricula on Materials Physics or Chemistry, Materials Science, Polymer Science, etc. In fact this approach relies on the investigation of the relationships that exist between the structure and properties of materials.

[5] Historically, before the 1960s (and in some cases decades after), many materials science departments were named as "metallurgy departments", from a nineteenth and early twentieth century emphasis on metals (Ferguson 2006). The field has since broadened to include every class of materials, including: ceramics, polymers, semiconductors, magnetic materials, medical implant materials, biomaterials and, more recently nano-structured materials.

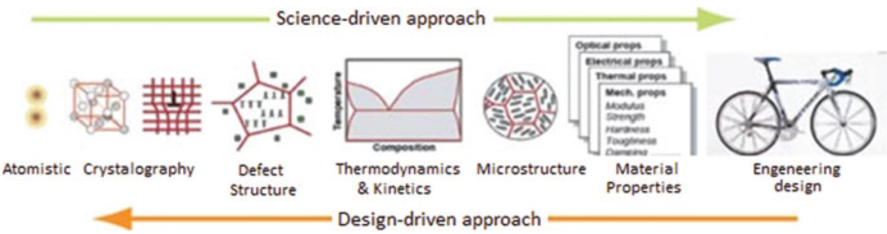

Fig. 7 Two approaches in materials science and engineering

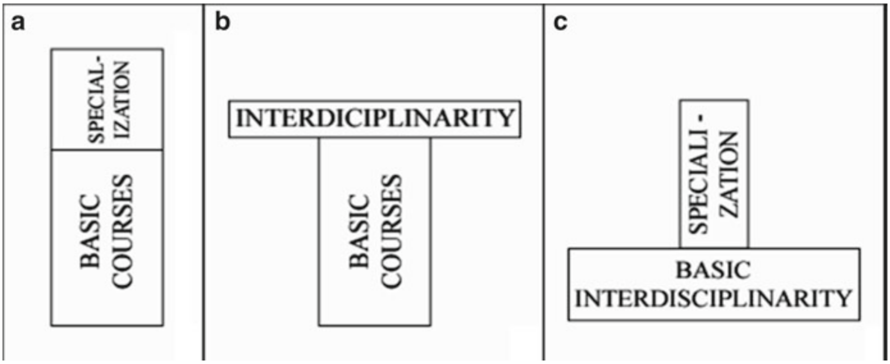

Fig. 8 Schematic of university education: (**a**) traditional scientific/engineering subjects, (**b**) interdisciplinary specialization (“T”), and (**c**) coherent curriculum (“Inverted-T”)

On another hand, in the *design-driven* approach, one seeks to design the structure of a material in order to produce a predetermined set of properties, based on the structure–property correlations. This approach is usually followed by Departments of Engineering, like mechanical, chemical or civil engineering, product design, etc.

3.1.2 University Level

Traditional university education is often represented as a straight line or as a sequential vertical progression from basic to specialized courses in a particular discipline (Fig. 8). In contrast, two different strategies can be seen for university education in materials sciences and in particular in nanoscience and nanotechnology. One emphasizes interdisciplinary specialization, and the other a coherent curriculum. For simplicity they can be referred to as the “T” and the “Inverted-T” approach (Deppert et al. 2008).

The first strategy, the T strategy, is a modification of existing educational programs. Conventional undergraduate courses in a traditional science or engineering discipline are followed by interdisciplinary specialized courses (Roco 2005). Normally, specialized courses are developed based on individual (or collective) faculty research interests, and the need for graduate students to assist in such research.

Typically, such courses evolve over the years in a research environment designed for students who may enter a Ph.D. program. A clear alternative is the Inverted-T strategy where the students are introduced to the essence and interdisciplinarity of nanoscience from the very first day. By reversing the sequence of learning, authors claims that students can be trained to take a coherent view of nanoscience and can be motivated to learn the necessary basics in the traditional fields of science and engineering (Roco 2004).

3.1.3 Pre-university Level

At secondary education, things are less clear; with the words “materials science” one can address different but inter-connected disciplinary fields. One field is defined by a somewhat new academic discipline aimed at the development of new solid materials for the technological needs of our society. For this kind of approach a basic knowledge of Physics and Chemistry is needed, in particular concerning the macroscopic properties (known and desired) of materials (mainly solids) and the microscopic models (structure) that explain the known properties and are the basis for a change toward the desired ones. When it comes to Genetic Engineering, Bioengeneering and Biotechnology, one needs a basic knowledge in Biology and Chemistry in particular concerning the macroscopic properties of biological systems and the microscopic models that are the basis for a change toward the desired properties. Materials Science in secondary education could be addressed in courses of science and/or technology. However, basic knowledge in physics, chemistry and biology is missing, or to be gained in the pre-university education. For this reason, instead of “materials science” (in the sense of studying the relationships between the structure and properties of materials) another approach is adopted – “science of materials”. In the science (or technology) of materials, technological applications are connected, as examples, with macroscopic properties of materials, and in some (rare) cases, with the microscopic models that are used for their explanation. This approach is found in many curricula and pre-university textbooks. An example is given in Fig. 9.

Figure 9 (left) shows a hot cube of a novel ceramic aero-gel material held with bare hands. The explanation is found in the figure caption which states, “The cube shown has just come out of the oven. The material which is made up mainly of air and is an excellent insulator, so although the temperature inside is close to 1200 °C, one can safely hold it from it’s the edges” (Antoniou et al. 2010). As can be seen, the type of material (ceramic aero-gel) is not mentioned, as well, as any reference to particular material structure, and hence it sounds rather unreasonable how a solid can be composed “mainly of air”. Understanding on this figure could be enhanced, if notion on the particular structure was given, as for example, in right figure.

In reference to Fig. 7, the attempts to deal with materials in secondary education curricula, in the framework of “science-driven” and “design-driven” approaches may be summarized in the following scheme “concepts – material properties – technological artefact.” A *science-driven* approach starts from concepts (e.g., the trans-

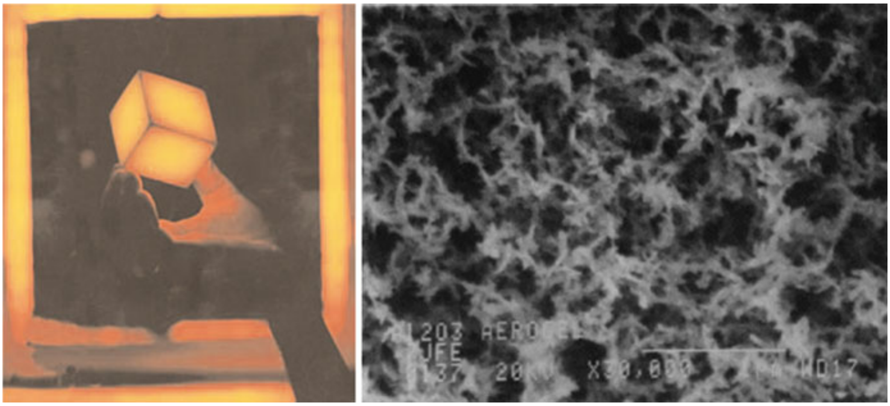

Fig. 9 Typical example for "technology and materials" approach in Greek high-school textbooks (*left picture*), which can be enhanced with reference to material structure (*right picture*)

fer of heat), passes to properties (thermal conductivity of material) and end to the technological design (material aero-gel). On another hand in the "*design-driven*" approach a technological problem is posed at first (e.g., thermal insulation of a house) which is dealt with through a combination of concepts and material properties. In either case, there is seldom a connection between materials' properties and materials' structure.

3.1.4 Introducing Materials Science in Pre-university Level

Clearly, a thorough approach to introduce Materials Science in pre-university level should require a change in curricula and text-books. Materials Science is, on the other hand an advantageous subject for inquiry-based teaching, as it connects structure and properties. Aspects of Materials Science, like nanoscale-science and engineering, is one topic currently being investigated as a way to increase students' interest in science due to its integrated nature and increasing popularity in society (Hutchinson 2007). Therefore, attempts have been made to introduce materials science as small-scale changes in existing curricula, in the framework of the Educational Reconstruction model (Duit et al. 2012, and references there-in).

Both design-driven as well as science-driven approaches have been adopted in the case study section of this book. In the former cases are approaches from a technological problem, like the acoustic isolation of a discothèque to discuss the acoustic properties of materials (Hernández and Pintó 2016, in this volume) or the uplifting a sunken ship to discuss the influence of density on floating/sinking (Zoupidis et al. 2016, in this volume). In the latter approach, concepts of reflection and refraction were used to introduce the optical properties of materials and fiber optics (Monroy et al. 2016, in this volume) or electromagnetic properties to magnetic trains (Constantinou et al. 2016, in this volume).

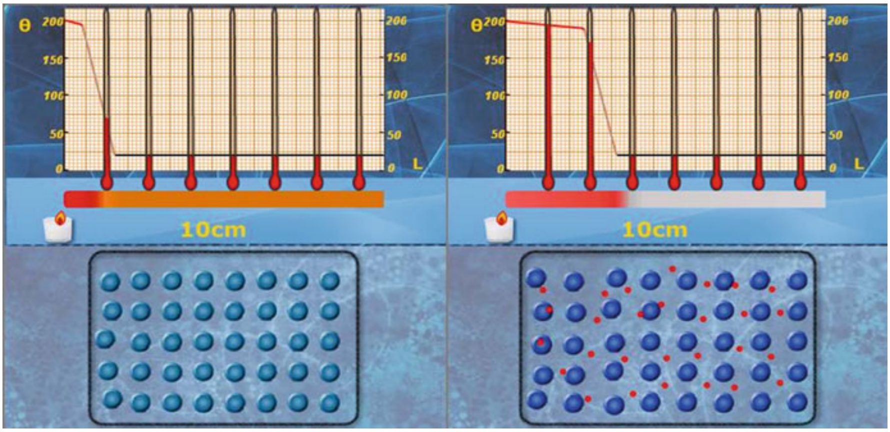

Fig. 10 Typical example of a screenshot of the teaching-learning module for thermal conductivity for a crystalline solid (*left*) and ametal (*right*)

A unique approach to enhance the connection between material properties (thermal conductivity) with material structure, adopted by the University of Thessaloniki, is depicted in Fig. 10. The screen is divided into two parts, the macroscopic model (top) and the microscopic (structural) model (bottom). Rigid balls, arranged in a matrix simulate the atoms in a lattice for a crystalline solid (left part) while small red balls represent the motion of the free electrons in a metal (right part).

Clearly, concepts of heat transfer in the above example should be first de-contextualized from scientific level, didactically transformed, and re-contextualized onto the cognitive level of the students. Such a de-contextualization/re-contextualization has been adopted. In order to introduce the material structure at microscopic level, the traditional concept of caloric heat flow, which students are familiar with, has to be replaced with the kinetic model. The connection and transition between the two models, the caloric, to and the new (kinetic) is done by putting them together on screen (top and bottom panel in Fig. 10). Atom balls vibrations are more rigorous in the hotter part than in the cold one. This approach helped students, who were able to distinguish between heat transfer in metals and insulators, as well as denser versus less dense ceramics and provide reasoning on the basis of their structural differences (Psillos et al. 2016, in this volume). Similar de-contextualization and re-contextualization have been adopted to discuss the acoustic properties of materials, the reflection / refraction, the influence of density on floating/sinking and the electromagnetic properties, found in the case studies in this volume.

The rapid development and growing societal importance of nanoscience and nanotechnology (NST) have evoked educational concerns throughout the world. Their growing socio-economic potential has attracted substantial investments from both the public and private sectors. Products of nanotechnology have started to invade the markets. A mounting need for education in this emerging field has been recognized not only at the academic level but also in terms of citizens' abilities to deal with personal, social, and global issues related to NST. Some understanding of NST has been postulated to be relevant in up-to-date scientific literacy for all (Laherto 2012).

Due to this development, NST has also become an interesting and important field from educational perspectives. Calls for nanoscience education have been made not only with regard to the academic level: several agencies have argued that the contents of NST should already be taught in compulsory education, and the general public's awareness of and engagement in these emerging fields should be promoted. Such demands have been made by public administrations, industry and commerce, civic organizations, scientists and engineers, teachers and educationalists, and social scientists (Laherto 2012).

3.2 Informal Education

Materials Science and the emerging field of nanotechnology seem to be of quite importance for general public's awareness. Furthermore Materials Science is an advantageous field for inquiry-based interventions. However the lack of a "materials science" based approach in existing curricula has made several organizations to attempt to introduce materials science in high-school level. Most of these attempts were made out-curricula, in science clubs, for example an attempt by Princeton University in inspiring 1,000 Middle School Students to Materials Science and Engineering (Steinberg and Swilley 2008). Another example is the Department of Materials Science and Metallurgy at the University of Cambridge, where, since 2004, initiated a Summer Programme, funded by UK Centre for Materials Education (Taylor and Mannis 2008). This involved staff working in partnership with students to develop e-learning resources: resources which have achieved international recognition for their quality and educational value.

Other approaches used sophisticated modern equipment, usually used in the study of materials. Fitzsimmons et al, for example, introduced students to SEM and AFM techniques,[6] and compared students' learning versus standard textbook/lecture techniques (Fitzsimmons et al 2006).

In the field of nanotechnology, the *Time for Nano Project* aims at engaging the general public, with a special attention to young people, on the benefits and risks related to nanoscale research, engineering and technology, through specific informal education products. Science centers in many countries in Europe organize "Nanodays," events with demonstrations, experiments, games, meetings, and discussions about nanotechnology. Students from high schools in these countries can participate in the *Time for Nano* video contest, a competition to produce the most

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[6] *Scanning Electron Microscope* (SEM) is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons.

Atomic Force Microscopy (AFM) is a very high-resolution type of scanning probe microscopy. The AFM consists of a cantilever with a sharp tip to scan the specimen surface and reproduce the morphology of the surface.

creative, scientifically sound, through provoking video on the dilemmas posed by nanotechnology (TimeforNano).

In all these cases, education outreach partnerships between science and engineering research organizations and schools were made, providing schools more robust opportunities for increased engagement with current research and how-to-do in the field of Materials Sciences. Similarly, informal science education institutions, such as science museums, can help research organizations to fulfill their "broader impacts" criteria as well as to advance their institutional interests in forging meaningful connections through the community (Alpert 2008). All these approaches share one common aspect: the way of teaching, which converts traditional labs (on materials) to project-based learning, aiding students' development of higher-order cognitive skills. In fact, materials labs are much favorable for inquiry-enhanced learning.

Recently, several projects are running in US as well as EU, attempting to introduce Materials Science and Engineering in out-curricula secondary education. The main reason is that often during the formative years students develop an interest or aversion to specific fields, which can influence their career choices (Fennema 2000). Thus, the National Science Foundation (NSF)-funded Renewable Energy Materials Research Science and Engineering Center at the Colorado School of Mines is involved in a K-8 outreach partnership directed at maintaining students' interest in science and engineering through hands-on activities in their classrooms (REMRSEC Site).

Materials researchers at Northwestern University and science teachers jointly authored 16 modules, in *Materials World Modules*. The Materials World Modules are examples of inquiry- and design-based learning in materials-related curricula for middle and high-school students. The modules include polymers, ceramics, composites, biosensors, dye solar cells, nanotechnology, and environmental catalysis. Each module has three parts: a "hook" that captivates student interest and inspires inquiry; exploratory activities that provide background central to the topic; and design projects that challenge students to apply what they have learned by creating functional prototypes from the materials at hand. This hands-on approach demonstrates the relevance of materials science, inspires interest in materials-related careers, increases students' confidence and enthusiasm, and builds essential workforce skills such as creativity, critical thinking, innovation, and teamwork (MWM Site).

3.2.1 Teaching Resources

Several teaching resources are available, free or commercial for the field of Materials Science. Resources are available at all levels of education, from compulsory to master's level. In most cases, resources include inquiry-based activities for connecting structure to properties of materials and nanosciences/nanotechnology.

The National Resource Center for Materials Technology Education (MatEd) is an NSF funded center housed at Edmonds Community College. MatEd is developing a clearing-house of teaching materials including labs, hands-on demonstrations, modules, and papers, which can easily be integrated into a variety of courses, classroom settings, and industry. The MatEd collection is expanding rapidly with peer reviewed, classroom tested educational materials (MatEd Site).

The www.whystudymaterials.ac.uk website is designed to increase understanding and awareness of Materials Science. The website has been created both as an informal guide to the world of Materials, and importantly as a teaching aid for use in secondary-level education. There are a number of interactive games, quizzes, and movies on the site, ranging from virtual tours of cars, football boots, and aeroplanes, to ships, CDs, and Stealth aircraft. The site also hosts video interviews with university students, information on related university courses, open days, and career opportunities to help younger students make informed choices about their futures (WSM Site).

Apart from sites and projects, software has been developed for the introduction of students to Materials Science. For example, *MATTER* has been producing CD-ROMs and interactive web sites designed specifically for school science, since 1997. MATTER was originally set up to produce computer-based learning software for undergraduate materials science and engineering. Materials MATTER in Schools – interactive CD-ROM – was designed to help pupils at key stages 3 and 4 with a number of important materials-related concepts in the national curriculum for science (MATTER Site). *Materials Interactive* is another example of resources designed and created to help increase the awareness of Materials Science and Engineering. This CD-ROM (currently PC version only) is freely available to all in education, but is generally targeted for use with 14–19 year olds.

4 Concluding Remarks

Materials Science is an interdisciplinary field involving the relationships between the structure of materials at atomic or molecular scales as well as their microstructure and their macroscopic properties. Materials Engineering, on the other hand, deals with the design or engineering of a material, on the basis of these structure–property correlations, to produce a predetermined set of properties. The aim of this chapter is to give a brief, yet comprehensive overview on the current challenges and advances in Materials Science as well as to outline attempts made world-wide to introduce Materials Science in secondary school curricula.

In recent years we have witnessed unexpected technological advances thanks to the progress of new advanced materials. New ceramics, polymers, metal alloys, bio- and hybrid materials have substantially improved our quality of life through new and better products and services, generating wealth and employment. From medicine to the aeronautic and information sectors, these new materials have contributed to radically changing our way of life. It is certainly true to say that materials are shaping our society.

Materials determine our environment – our world. Materials Science and Engineering, are key drivers behind almost all major technological advances and breakthroughs; for example, photonic components and solid state lasers for communication technologies, Li-ion batteries for energy storage, and the performance enhancements in microelectronics. Advanced materials and advanced engineering also set the stage for the technology-based innovation of tomorrow. The societal challenges of urbanization, resource depletion, and climate change, for instance, call for a cleaner, more efficient, and more sustainable economy. In turn, the efficient use of resources and energy is becoming a key challenge of the twenty-first century. Recent developments in material processing demonstrate the potential that advanced processing technologies hold for the future: high performance structures and composites for products that are more energy efficient, less waste-related, better for recycling, creating more sustainable value chains. Materials Science and Engineering can provide effective solutions. Advanced Materials and Materials Engineering create new sustainable environments.

Nanoscience and Nanotechnology, on the other hand, were treated not as standalone topics, but as a promising and essential approach to develop new materials and exploit new properties.

Nanoscale features can influence the phenomena and applications of the macroscale. Their potential for characterizing and building up nanostructures will meet ambitious goals in all sectors. Imagine for example a supercomputer based on nanochips would comfortably fit in the palm of your hand and use less electricity than a cottage. Nanoscience and Nanotechnology will also have the merit of bringing together chemists, physicists, biologists, medical doctors, sociologists, etc, in a multi-disciplinary approach.

Modern Science stands at the beginning of what might seem by today's standards to be, an almost magical leap forward in our understanding and control of matter, energy, and information at the molecular and atomic levels. Atoms (and molecules or structures they form through share or exchange of electrons) are the building blocks of the biological and non-biological materials that make up the world around us. In the twentieth century, scientists continually improved their ability to *observe and understand* the interactions among atoms that determine material properties and processes. Now, scientists are positioned to begin *directing* those interactions and controlling the outcomes on a molecule-by-molecule and atom-by-atom basis, or even at the level of electrons.

Materials concepts can be taught at all grade levels if the information is adapted to the appropriate cognitive level. Qualitative behaviors of different materials can be introduced in the early grades, with more complex material properties, connection to structure/microstructure and quantitative measurements coming later.

Clearly, concepts and ideas of Materials Science should be first de-contextualized from scientific level, didactically transformed, and re-contextualized onto the cognitive level of the students. An approach could be the development of a comprehensive high-school science program that uses the inherent multidisciplinary framework of materials science and materials engineering to unite the disciplines of physics, chemistry, biology, and geology, in the STEM-oriented curricula.[7] Beyond the STEM-based curricula, in more traditional educational settings, Materials Science concepts may be introduced by making links of material properties to materials structure and/or microstructure, as for example the aerogel in Fig. 9, the carbon fibers in tennis rackets, etc.

[7] STEM stands for Science-Technology-Engineering-Mathematics.

Materials-related instructional curricula have been developed and made available, as for example the Materials World Modules (MWM). However, they have not been widely adopted in middle and high schools and there are many possible reasons for this limited success. MWM is based on a two-level cycle namely, inquiry-based and design-based learning, which makes modules much more in demand with time-intensive activities requiring 1–2 weeks for each module, which might not be the best match with an average classroom. Another possible obstacle could be the complexity of each local K-12 system, which includes state standards and local control of the curriculum.[8]

Clearly, there are still challenges to meet in introducing Materials Science both in primary and secondary education. One of these challenges may include the teacher professional training, as teachers in primary and secondary education often seem to have little understanding of how their subjects connect with materials science and materials engineering. Consequently, there is little or no systematic discussion of materials in classes taught by this cadre of teachers. However, several projects offer out-curricula activities in an attempt to introduce high-school students to Materials Science. These projects may help to increase the student interest in science and engineering in general, and materials science and engineering, and, consequently to increase the public awareness of the discipline and its critical role in solving societal technological challenges.

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Integrating Science and Technology in School Practice Through the Educational Reconstruction of Contents

Italo Testa, Sara Lombardi, Gabriella Monroy, and Elena Sassi

1 Introduction

There is a growing consensus amongst Science Education researchers that complex challenges of industrialized societies demand curriculum designers to empower students with conceptual and practical tools to let them become active citizens and not only passive consumers of knowledge products (DeBoer 2011; Bencze and Carter 2011). These tools have been grouped under the 20 or more years old slogan of Scientific Literacy (SL). According to Sadler and Zeidler (2009),

> the phrase has become ubiquitous in our field and represents what we expect students to know and be able to do as a result of their science learning experiences. (p. 910)

Roberts (2007) divides into two broad categories the manifold conceptions of SL:

1. The first (Vision I) promotes the learning of de-contextualized science knowledge (i.e. concepts, processes, structure) and is essentially related to traditional approaches where scientific contents come first, while some brief reference to applications are made at the end (Bennett et al. 2003). These approaches have gained some criticism since they may transmit a distorted and impoverished view of science which can negatively affect conceptual learning (Gil-Pérez et al. 2005).
2. The second (Vision II) entails those approaches which aim at helping students develop and master high-level reasoning skills as decision making (Sadler and Zeidler 2005a), argumentation (Jiménez-Aleixandre and Pereiro-Muñoz 2002), reflective judgment (Zeidler et al. 2009) in order to use scientific knowledge in

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different science-related contexts of their own life (health, environment, …). Vision II is therefore basically related to a situated learning perspective in which: *"knowing and learning cannot be abstracted from the environments in which they take place"* (Sadler 2009, p. 3).

We clarify that the key distinction between Vision I and II relies on the word *context* since it focuses, rather than on Science inner world, on the relationships between Science and the real world.[1] To the widest extent, society *is* the broadest context in which Vision II of SL may fulfil its aims since decision-making, argumentation and reflective judgment are all activities that make sense when a plurality of individuals share a common background and are called to deal with controversies in a non-violent and cooperative way. However, relationships amongst individuals and between individuals and Society are increasingly mediated (for instance, in communication processes) by Technology, which shares a reciprocal help relationships with Science. As a consequence, the meaning of *context* – an important aspect of SL Vision II – can be extended in a continuous manner by including the connections – Science, Society and Technology.

The Science-Technology-Society (STS) movement (Ziman 1980) started in the late seventies as an answer to dissatisfaction with some aspects of previous curricula reforms in science education (Fensham 1988) and purposefully addressed the interplay between Science, Society and Technology. Main aims of the STS curriculum were (Aikenhead 2007): to bridge the gap between science contents in the curricula and students' interests[2] in everyday life; to focus on the nature and image of science and of the scientific intellectual enterprise; to give high priority to students' preparation for a responsible and informed participation as citizens in social decisions involving scientific and technological themes[3] as environment, sustainable development and health.

[1] Science *is* developed by scientists within the real world and its main objective is the study of natural phenomena which happen in the real world. However, science knowledge is developed using the abstract language of mathematics and hence in its theories, models and processes are de-contextualized. The aims of such de-contextualization are to acquire the necessary level of reliability (Ziman 1978). We will return on the issue of reliability in Sect. 2 of this paper.

[2] Here "interest" is intended as an intrinsic motivational variable with three specific aspects: it is content specific; it is the result of an interaction between an individual and the surrounding environment; it has both cognitive and affective aspects (Lavonen et al. 2005; Hidi et al. 2004). For the sake of brevity we will not address the interest issue in this paper.

[3] A wider meaning to the students' participation to society as active citizens as far as Science and Technology are concerned is the dimension of professional careers. Recently Europe has witnessed students' waning interest in science and technology related careers (European Commission 2007; Nuffield Foundation 2008). There are many factors influencing the choice of a professional career as for instance (Lavonen et al. 2008): perceived values and images of Science and Technology; stereotypical views of scientific and technological occupations; perception of the difficulties about physics and mathematics; socio-cultural environment; quality of science and technology curricula; gender gap. For an overview of Italian students' choices of scientific studies at academic level see Pellegrini (2011). Although it is in some way related to the arguments of this paper, for the sake of brevity, this theme is not addressed here.

The STS movement pervaded the science curricula reform agenda until the mid nineties and later generated educational sub-movements, as STSE (E stands for environment)[4] and SSI (Socio-Scientific Issues).[5] STS approaches are somewhat diffused mainly in countries where didactical proposals were designed (e.g. the PLON project in Netherlands, Salters Advanced Chemistry/Physics in the UK, and Scope, Sequence and Continuity in US; for an extensive review see Aikenhead 2003) but they are still somewhat marginalized from the curriculum in other countries (Hughes 2000). In our opinion, this is related to the question: "do students *actually* learn Science through STS, STS(E) and SSI approaches?". Results from literature so far are somewhat contradictory. Bennett et al. (2007) claims that:

> the findings on understanding of science provide strong evidence that context-based/STS approaches provide as good a development of understanding as more conventional approaches. There is more limited evidence to suggest that understanding may be enhanced. (p. 16)

Aikenhead (1994a) also admits that:

> student achievement on traditional subject matter at the next level of science education (at a higher grade or at university) will not be significantly compromised by teaching science through STS.

Therefore, STS designers experienced a kind of *frustration* of their initial expectations:

> …one lesson that we learned as curriculum developers is that, in general, issues were dealt with [in the PLON project] too broadly. We were seduced in our first version materials in trying to deal with a complete issue, such as the Energy Problem or the Nuclear Arms Race. (Eijkelhof and Lijnse 1988, p. 467)

The issue is becoming more relevant in a world dominated by standardized assessments: poor results in students' achievements (OECD 2009; IEA 2011; NAEP 2011) may be really a valid reason to impede the diffusion of these movements in school practice.

Limiting the focus to the relationships between Science and Technology in the prospective of the implementation in school practice, from what discussed above, the following research questions arise:

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[4] The STSE movement aims at: promoting students' awareness of cultural aspects of Science and Technology; discussing the role of economics in scientific and technological decision; development of students' own ideas and values about scientific and technological progress; promoting active and conscious agency in society and politics (Pedretti and Nazir 2011).

[5] The SSI movement promotes students' involvement in learning science through controversial contexts that concern society (Sadler 2004). The dilemmas usually are embedded within a complex web which requires content knowledge related reasoning and arguments, explicit reflection on relevant epistemology aspects, personal connections at micro- (familiar), meso- (state citizenship) and macro- (human perspective) level with the issues. Consequently, to deal with SSI, environmental, economical, political, moral and ethical considerations are needed in order to provide students with opportunities to prepare them to act as active contributors to the life of the society which they live in (Zeidler et al. 2005).

- RQ1. What contents should be taught in approaches aimed at implementing an integration between Science and Technology?
- RQ2. How should these contents be treated to achieve an effective integration?

The aim of this paper is to answer to these questions by presenting and defending an overall framework which re-conceptualizes the Science and Technology integration at the educational level of Teaching-Learning Sequences (TLS, Meheut and Psillos 2004). A TLS embeds the close relationships between research and development of teaching activities at an intermediate level between the macro dimension of a curriculum and classroom micro-episodes. Two general aspects of TLS design and development, reviewed in the introductory chapter (Psillos and Kariotoglou, this volume), will be discussed in more detail here: (1) the epistemic dimension, to build the integration on important aspects of Nature of Science and Nature of Technology; (2) the reconstruction of content knowledge or didactical transposition, to identify a *common core* on which the Science and Technology integration is built. A third aspect, that of iteration as a means to improve and adapt an integrated TLS, will be the focus of our case study.

The structure of the paper is as follows: we first review previous efforts in integrating Science and Technology in educational research; then, we detail the main features of the proposed theoretical framework. Finally some teaching implications are discussed.

2 Previous Attempts at Integrating Science and Technology

While advocated from one hand as a central part of SL (AAAS 1989, 1993, 2001; NRC 1996; ITEA 2000), the role of Technology in science education seems controversial (Raizen 1997):

> STS courses developed by scientists and science educators express an entirely insufficient conception of technology. (p. 63)

So what is this not informed conception of Technology that emerges from science education approaches? Literature has revealed a wide range of approaches to deal with Technology from the perspective of Science Education.

Historically, STS approaches have followed the straightforward way of trying a balance between traditional science and more socially-oriented contents. This way of dealing inevitably leads to a loss of depth of the contents to be addressed. As reported by Aikenhead (1994b), two distinct but complimentary directions have been taken in developing curricula: on the one hand, the teaching of standard science contents embedded within a technological/social context to ‘spice’ them up; on the other hand, focus is mainly on students’ critical thinking and attitudes toward science with a scanty attention to science and technology contents. Combinations of these two viewpoints have resulted in a heterogeneous compound of standard science and STS contents.

Gilbert (1992, p. 570) identified a cluster of approaches which could be categorized as "*education involving technological outcomes*" and intervention focused on "*the processes by which those outcomes are produced*". The first category encompasses *content-driven* approaches, the focus being on the science content; the second one entails *process-driven* approaches and was focused on the technological design.

Gardner (1994, 1999) proposed a categorization of the views of the relationships between Science and Technology from the epistemological viewpoint: Science precedes Technology or Technology as applied Science (De Vries 1996); Science and Technology are independent, Technology precedes Science, Technology and Science learn from each other. Basically, many STS approaches use technology only as context both from the Science viewpoint (technological devices are applications of physics laws) *and* the Society viewpoint (in terms of the social consequences of the use of a technological device).[6]

Craft-based, industrial production-oriented and high-tech approaches[7] are all examples of the demarcationist view of Science and Technology relationships in which basically Technology is taught independently of scientific knowledge.[8]

Design-based approaches are on the side of an integrated view (for a review related to the UK context see, e.g., Wilson and Harris 2004). Design is basically a circular process which involves four stages (Cross 2003; Banks and McCormick 2006): identifying needs and opportunities (1); generating (2), implementing (3), evaluating and re-designing (4) the solution. There are many conceptualizations of the design process with a growing level of complexity (Rennie et al. 1992) but research has mainly focused on if and how this practice may help science educators to engage students in more authentic hands-on activities and tasks (Crismond 2001) to learn more science content (Roth 2001; Fortus et al. 2004).

[6] Lavonen et al. (2005) argue that the role of technology in STS approaches declined with time since it is problematic from the viewpoint of gender issues. The main argument is that girls do not perceive technology as interesting as boys, being more interested in society problems as sustainable development and environment respect. While valuing this perspective, for the sake of brevity, the theme of technology in STS instruction from the viewpoint of gender issues is not discussed here.

[7] In some European countries and in Australia, in early nineties, the term technology education was replacing the term "industrial arts" (De Vries 1994). Many questions surrounded this trend in curricula change: was this new subject industrial arts renamed? Did it reflect new instructional content or methods? Will a new student population be served? (Herschbach 1992, p. 4). Generally, there was a fairly common consensus about the need for the introduction of a sort of technology education, whose main aims were essentially (Gilbert 1992, p. 568) to: prepare students for work in the technology industry; provide general literacy in order to prepare technology fluent citizens; learn about how technology is organized and its consequences for society. The first aim was borrowed from the former 'industrial arts', whereas the other two were new and inspired by the just born debate about the nature of technology (AAAS 1989).

[8] An example of this view can be found in the secondary school curriculum in Italy where, at compulsory secondary level (14–18 years), scientific and technological/vocational school streams are separated both in terms of contents and public perception.

Some recent findings suggest that design activities integrated by exemplar experiments aimed at addressing students' alternative conceptions can be particularly effective (Schnittka and Bell 2010), while other findings suggest that design activities alone do not guarantee an improvement of students' achievements in science (Levinson et al. 1997; Penner et al. 1998; McRobbie et al. 2000; Silk et al. 2009; Puntambekar and Kolodner 2005).

The effectiveness of design activities seems thus basically demanded to the ability of teachers to manage such an increased cognitive load into their practice. And, in the best case, what can be obtained is a successful *inclusion* of design activities into Science classroom. As a consequence, echoing the popular debate started in the '70s about Combined Science, Coordinated Science, Multidisciplinarity vs. Interdisciplinary (Richmond 1973; Black and Atkin 1996; James et al. 1997), integrated design-based approaches have gained the favour of some authors (Lewis 2006) but also have raised some criticism in defence of a status of Science and Technology as separate subjects (Carlsen 1998; Barlex 2002; Lewis et al. 2007).

Recently, scholars of the Science and Technology integration (Geraedts et al. 2006) have realized that the debate was mainly on the *degree of integration* of the two subjects (Layton 1988). This lead to neglection of the multi-dimensionality of the integration process, which includes: ways of learning, ways of knowing, skills, content, attitude and pedagogy (Berlin and White 1994). These authors hence called for a more coherent approach to support the broad aims of SL (AAAS 1993) supporting especially awareness of the nature of constituting disciplines and mutual coherence. Similar programs had been already proposed on the basis of cooperation between science and technology teachers in Israel (Barak and Pearlman-Avnion 1999), US (Beven and Raudebaugh 2004) and in Canada (Bencze 2001) focusing on a sort of double-track of scientific investigation and invention/design projects.

However, all these approaches seem to be born from the strive for legitimacy in school practice of Technology (Lewis 2006):

> …as school subjects, Science and Technology have had separate existences – the former being well established and bearing high status, the latter striving for legitimacy as valid school knowledge, its status often insecure. (p. 255)

and from the somewhat "private competition" with Science refuelled in some way by many standard associations calls for improving Technology Literacy (AAAS 1989; ITEA 2000, 2003).

Hence, while some of these authors (Barak and Pearlman-Avnion 1999) support the view that the

> separation between the areas in school curricular is often artificial. (p. 239)

acknowledging that (Cajas 2001):

> there is a common body of scientific and technological ideas and skills that is relevant for the education of all students. (p. 725)

they do not deal directly with the central question from the educational practice of how to use this common body and, more specifically, what kind of contents the students would learn from these integrated subjects (Yager 1996) taught by different teachers with sometimes different academic backgrounds.

3 Main Relevant Aspects of the Nature of Science in the Perspective of Integrating Science and Technology

To discuss our approach to the integration of Science and Technology from the content knowledge viewpoint, some reflections on the prominent epistemologies that shape current views of Nature of Science (NOS) should be pointed out. As argued in the introductory chapter (Psillos and Kariotouglou, this volume), the epistemic dimension in the design and development of TLSs in science education allows to analyse the structure of the contents to be taught, their theoretical underpinnings and their historical evolution. For this reason, NOS has often been acknowledged as relevant in SL (NSTA 1982). In particular, advocates (Abd-El-Khalick and Lederman 1998; Bell et al. 2000) support the claim that a learning objective of science education for all students would be the awareness of certain important aspects of NOS. Amongst these, there is consensus on (Lederman 2007): tentativeness[9] of scientific knowledge and reinterpretation of stable knowledge when new evidence is available; empirical research is informed by theory but also by scientists' personal creativeness; scientific knowledge is socially constructed through the instrument of peer review and cultural norms agreed in the scientific community.[10]

While valuable, these aspects say little or nothing about what actually should or can be done for integrating Science and Technology in the sense that we adopt in this paper. Some more specific discussion about the chosen aspects should be elicited from the research field about NOS to deal with the integration issue. To achieve such specificity, we will use as exemplary disciplinary scientific context Physics.

The first aspect concerns *how* the contents are established within Physics body of knowledge. With respect to this aspect, basically we ground our position on the work by Ziman (1978). Being Physics purposefully developed to use an unambiguous language as mathematics, the theoretical constructions that describe and interpret the natural phenomena should include measurable quantities, i.e., quantities to which it is assigned a number, and hence, it is the choice of such quantities that warrants the reliability of the physics results. Conversely, the reliability of scientific descriptions, interpretations and prediction of natural phenomena can be judged by the fact if measurable quantities are involved in this process.

As any other fields in Science, also Physics has its tentativeness in the selective sense summarized by Ziman (1978):

> Only a small proportion of the information contributed to science by research is eventually incorporated permanently in the body of scientific knowledge. (p. 130)

[9] Tentativeness implies the existence of controversies amongst scientists that may arise, e.g., from discrepancy between theoretical predictions and experimental observations and can be resolved with plausible modifications to the theoretical assumptions or with the development of completely new frameworks for interpreting them.

[10] Recently, SSI advocates had also called for the relevance of ethical and moral considerations in the scientists' work (Sadler et al. 2004).

However, in the perspective of an effective integration of Science and Technology as envisaged here, contents should be established, otherwise they would not be immune to disputes and coherence flaws. A corollary to this assumption is that measurable quantities are essentially the *key ideas* (see below) needed for reconstructing the content since in this way it is possible to guide the students to connect these quantities with natural phenomena which are valuable and relevant to investigate.

The corollary of measurability leads to the other two interlinked aspects of NOS that we consider important for the integration of Science and Technology: laboratory experiments and modelling. In this case we will shape our position on the work by Vicentini (2006; Danusso 2010). In both aspects, the key role is again played by scientists' choices, this time on a larger scale. S/he deliberately chooses what natural event to study and investigate: if the event is complex, after a first qualitative observation, quantitative parameters necessary for a mathematical description and interpretation of the phenomenon are selected. Such choice can be guided by theoretical considerations or attempts are made in order to achieve the necessary level of reliability of results obtained. A schema of this process is shown in Fig. 1.

We stress here the fact that such choice discriminates what is accessory to the phenomenon, and consequently negligible, and what is not: from such choice, a laboratory experiment will be designed and carried out to collect data to be analysed in order to construct a *scientific model* of the investigated phenomenon. Scientific models can be inserted into a wider schema (theory) useful to describe, interpret and predict different phenomena. More specifically, models are developed to respond to questions as: "how the phenomenon is manifested?", "how can it be reproduced and interpreted?". A relevant role in the process of integration of Science and Technology will be played by model's components and functions (Bunge 1973;

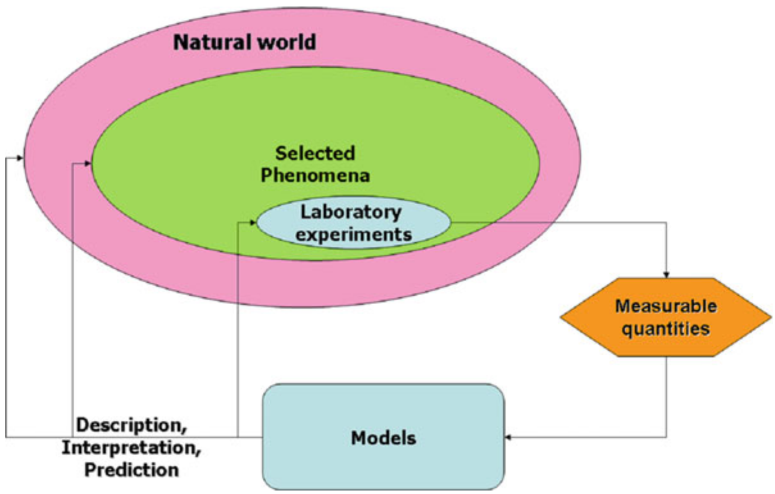

Fig. 1 Schema of the discussed NOS aspects for the generation of reliable knowledge (Adapted from Vicentini 2006)

Hestenes 1992): the components are the ensemble of the chosen measurable entities and of the law statements, validated by experiments, that relate them; the functions are basically the prediction and explanation of the observed phenomena.

For many readers, it is not difficult at this point of our discussion to envisage how the reconstruction of the content in terms of basic measurable quantities, which are the building blocks of the scientific knowledge, could play a central role in the integration of Science and Technology. However, we still need to specify how these aspects of NOS interact with specific features of the Nature of Technology (NOT) to give rise to a meaningful integration of Science and Technology. In the next section we will build on a new conceptualization of NOT in order to define the most relevant aspects for this integration.

4 The Nature of Technology: Some Uncharted Aspects

Previous review studies (e.g., DiGironimo 2010) show that consensus about important aspects of Nature of Technology (NOT) is yet to be reached. For instance, a definition of Technology can be found in every dictionary and the interesting issue is that each dictionary nearly gives a *different* definition.[11]

Basically, Technology can be knowledge, applied science, technique (or set of techniques), practices and art, or a "distinctive human achievement" (Gilbert 1992, p. 564). Also the Project 2061, in its *"Science for All Americans"* on-line document,[12] is rather scanty in giving any precise definition of Technology suggesting that it is a body of techniques that grew over the centuries establishing a unique and privileged relationship with Science to solve practical problems and enlarging the body of scientific knowledge. The Project 2061 document clearly puts into the front the relationship between Science and Technology but does not explain why such relationships should exist. While important to build integration between them, this relationship should be better clarified starting from a sounder definition of what is Technology.

Our position is built on the basic structural principles described by Arthur (2009): every technological object or device can be seen in a broader sense as a system with a given finality and built on several components (combination); every component is a technological object itself, even the most elementary part (recursivity); every technological object internally exploits a physical principle strictly related to a natural phenomenon (harnessing). The combinatory structure of technologies is depicted in

[11] For instance, from the Cambridge Dictionary:

> science is the knowledge obtained from the systematic study of the structure and behavior of the physical world, especially by observing, measuring and experimenting, and the development of theories to describe the results of these activities; technology is the study and knowledge of the practical, especially industrial, use of scientific discoveries.

[12] On-line http://www.project2061.org/publications/sfaa/online/chap3.htm accessed September, 19th 2011.

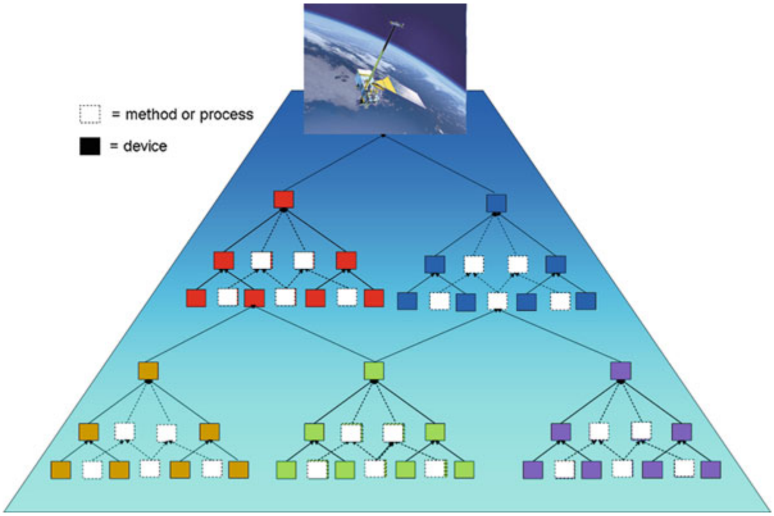

Fig. 2 A technological object seen as recursive combination of several technological components

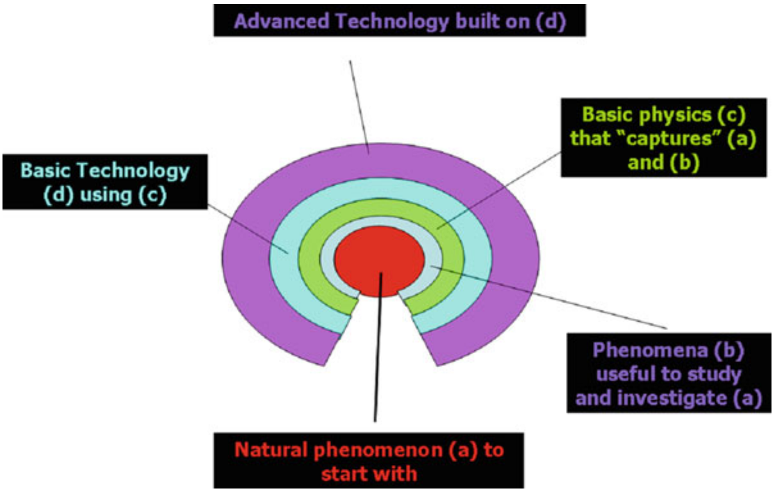

Fig. 3 Progressive harnessing of a natural phenomenon to be exploited by a technological object

the schema in Fig. 2. The process of harnessing and exploiting of natural phenomena is represented in Fig. 3.

Figure 2 shows that a technological object (for instance, a geostationary satellite) is the result of a complex tree-like structure in which technological processes and devices are suitably combined together into finite lower-level technological objects/process. These, in turn, are the result of the combination of other lower-level objects and so forth. Figure 3 shows how a single lower-level component of the tree-like structure of Fig. 2 is built. At the very heart of every technological object or device there is a single natural phenomenon (or a set of phenomena). This is easily recognizable from examples in the field of real-time measurements (Thornton and Sokoloff 1998; Sassi 2005; Sokoloff et al. 2007): a temperature probe uses a thermistor, i.e., a resistor whose resistance decreases nonlinearly with increasing temperature; a version of the force sensor is based on the Hall Effect; the motion sensor uses ultrasound waves echo. The phenomenon can be studied and interpreted using empirical laws and mathematical models. These abstract representations allow to reconstruct, in a controlled setting, the conditions for the phenomenon to happen in order to build a technological object or outline a technological process. Now the harnessing is complete and lower-level components will then be used to build higher-level components in the tree-like combination depicted in Fig. 2. More complex examples are reported by Arthur (2009).[13]

The adopted view warrants reliability to a sound Science and Technology relationships, given as an inevitable matter of fact in the Project 2061 document. Conversely, this view also warrants the role of Technology in SL: Technology builds on Science to discover and harness new useful phenomena while Science is based on Technology because of instruments, methods and experiments useful to investigate and reliably describe and interpret these phenomena.[14]

The adopted view also clarifies the role of another important aspect of NOT, i.e. technological design. It is the mechanism to build new technological objects by recombining and adapting existing ones. Design therefore is at the basis of the evolution of Technology, triggered by the quest for suitable solutions to a given aim using a repertoire of skills and resources which successful professionals manage and increase with time.[15] This view justifies the research findings (Sect. 2) according to which design activities can be considered pedagogically valuable to foster students'

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[13] This view is not in contrast with historical progression of Technology: some phenomena can be evident (e.g. the fire when rubbing small wood pieces), others can be much hidden and need more effort to be harnessed in a specific technological device (e.g. quantum effects). As pointed out by Arthur (2009):

> Science is indispensable to discover the most hidden phenomena, to create technologies that exploit them; moreover, it furnishes the conceptual instruments to observe these phenomena, the necessary knowledge to elaborate them, the theories to explain them and predict their behaviour, and often the methods to harness and exploit them.

[14] Another reason for which Technology cannot be simply viewed as applied science is the fact that most of the technological objects are very "far" from the original phenomenon on which each of their components has been built on. While taking advantages of the progresses of Science in describing further phenomena useful to capture the original phenomenon, these advanced technological objects have mainly built on existing ones exploiting the recombination mechanism at the basis of the evolution of Technology.

[15] In this view, to design means basically choosing solutions that must take into account available technological components as well as economics constraints. As scholars have suggested this makes creative problem solving an essential feature of design (e.g. Williams et al. 2008). As the design process, creative problem solving features: formulation of a problem, identification of goals and evidences related to the problem, evaluation of different possibilities, choice of the solution, test-

creative approaches to scientific and technological contents and engage them in authentic practices (see also, e.g., Benenson 2001; Stein et al. 2003).

Finally, because the scientific endeavour tends, since its birth (Galilei 1623), towards a given aim – i.e., the acquisition of reliable knowledge of natural phenomena (see Sect. 3) – a parallel between technological design and scientific modelling can be set up: as design allows to draw new technological objects from pre-existing ones, the modelling process allows scientists to build on seemingly independent components (variables and their relationships) to construct the description and interpretation of phenomena. *This parallel demands a renewed meaning to the integration of Science and Technology from the educational viewpoint: not a simple inclusion of activities from one field to the other but a completely new way of dealing with contents and methods to be used in the teaching/learning activities.*

Specifically, the idea of identifying the root of each technological object in a natural phenomenon is the conceptual pillar of the Science and Technology integration proposed in this paper: given a technological object or device, it should be first de-constituted of its components and the basic phenomena which it harnesses have to be identified; then, key ideas are identified and measurable quantities are related to these phenomena. In this way, it is possible to identify a Science and Technology common core, which is the object of the disciplines' integration.

However, to systematically derive this common core, an educational framework in which Technology and Science contents are *reconstructed* is needed. This process will be detailed in the next section.

5 A Framework for Integrating Science and Technology from the Content Knowledge Viewpoint

In Sects. 3 and 4, we inferred from the reviewed literature the basic need for an effective Science and Technology integration, namely, to *reconstruct* Science and Technology contents for educational purposes. This is not a matter of choosing an existing Science or Technology content that can be addressed focusing attention alternatively, according to the most up-to-date educational trends, to the Scientific or the Technology knowledge. Most of textbooks do so and they basically fail to give an informed idea of the relationship between Science and Technology (Gardner 1999).

As already pointed out in the introductory part of this article, some issues about the Science and Technology relationships have not been completely solved. In all these approaches, the close relationships between Science and Technology is acknowledged because these are already embedded in the complexity of modern western society and almost given for granted without any theoretical justification. More specifically, the contents addressed in these approaches are basically those addressed in traditional curricula and even approaches purposefully developed to

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ing and evaluation. Skills required for students to engage successfully in this process are: criticism, system analysis, divergent and lateral thinking.

struggle against the "*tyranny of school science*" (Bencze 2001) lack of a suitable attention to what kind of contents should be addressed.[16]

Basically, our view of integration emerges from the *elementarization* of a given broad *theme* in terms of two NOS and NOT content-related aspects that we have discussed in the previous two sections. Examples of such themes are, for instance: sensors; audio amplifiers; rockets; radio transmitters and receivers; circuits for the control of train traffic (see also Barak and Pearlman-Avnion 1999; Bencze 2001; Gardner 1999). We will give more details about the process of elementarization in Sects. 5.1 and 5.2. Here, we want to stress that the identified theme should feature a scientific content-related *component* and a technology-related *component*. These components are characterized respectively by:

1. Key ideas at the basis of a Science content
2. A natural phenomenon at the basis of a given Technology

Usual Science and Technology integrated teaching emphasizes alternatively one of these components (e.g., Barak and Pearlman-Avnion 1999; Geraedts et al. 2006). In our approach, on the contrary, first both components should be *reconstructed* for didactical purposes: the scientific part should be elementerized so to identify key ideas at its basis; similarly, the technology component should be elementerized so to identify the technological process or device to which it refers and then the natural phenomenon that this technology harnesses should be identified. At this point one can integrate the enucleated key ideas and natural phenomena in form of a single common core and proceed through the teaching using the authentic practices of scientific modelling and technological design to fulfil the intended learning outcomes. We will provide two working examples of our approach in Sect. 6.

The *reconstruction* dimension, also called in literature didactical transposition, has often informed design frameworks as those developed by the Leeds or Lyon groups (Psillos and Kariotouglou, this volume). However, due to our focus on the conceptual structure of content knowledge, we chose the Educational Reconstruction (ER) model (Kattmann et al. 1995) as suitable framework to carry out the identification of scientific key ideas and of natural phenomena which are harnessed by a technological device or process. After a very brief description of the framework (more details are provided in the introductory chapter), we will discuss in depth why this framework could usefully guide the process of Science and Technology integration.

5.1 The ER Model

The importance of the *reconstruction* of science content for educational purposes is well established in the German tradition of "*Bildung*" and "*Didaktik*", concepts whose English translation is difficult. The English term "formation" does not

[16] Obviously, we do not assert that these efforts fail to adhere to their own view of framing the integration of Science and Technology but only that they reflect a view of integration that resembles a rather simplicistic way of putting together Science and Technology contents.

completely convey the meaning of "Bildung", i.e. the psychological, educational and cultural development of the learner as a whole person. Similarly, "Didaktik" has a much wider meaning than the English "didactics", which essentially refers to issues of educational practice. "Didaktik" is linked to "Bildung". In German, it means transforming disciplinary or cultural knowledge into a knowledge form suitable for teaching and aimed at contributing to learner formation ("Bildung"). The teaching process is viewed as being composed of two closely interrelated phases: "*elementarization*", where key elementary ideas of a specific content are identified; and "*construction of the content structure for instruction*". Major reference of Educational Reconstruction is the "Didaktische Analyse" approach (Klafki 1969, 1995).

Epistemologically, the ER refers to constructivist viewpoints (Duit 2007): learning as a process of building one's own science knowledge starting from previous ideas, experiences, conceptions and knowledge (Driver and Easley 1978); science as a social construction (Abd-El-Khalick and Lederman 2000).

Three interrelated components are featured in the ER (Duit et al. 2005):

1. The first component refers to clarification/identification of scientific ideas in the specific content from an educational viewpoint and to their educational significance ("elementarization" of the content). Here, the focus is on "key ideas", i.e., the basic concepts and phenomena that might help to transform the given content into one suitable for teaching.[17]
2. The second component refers to the analysis of students' and teachers' perspectives, alternative/naïve conceptions, affective variables, etc. that are relevant for the particular instruction.
3. The third component refers to the design of educational materials and activities at the core of the teaching-learning sequence. Here content reconstruction materializes in the design of activities to help students understand the scientific contents.

5.2 Use of the ER Model to Integrate Science and Technology

The ER framework refines the rationale for designing teaching/learning aimed at effectively integrating Science and Technology (Fig. 4).

The starting point is the common Science and Technology theme. Then, the ER model allows identifying the key ideas underlying the scientific component of these contents (through the analysis of textbooks, epistemological studies, historical review, …). It is therefore possible to select measurable quantities and exemplar

[17] For instance, a key idea to start the teaching of electric circuits may be the concept of potential difference. Similarly, a key idea for the teaching of mechanical waves may be to address the fact that a small portion of a string perturbed by a transversal train-pulse, oscillates vertically around its equilibrium position.

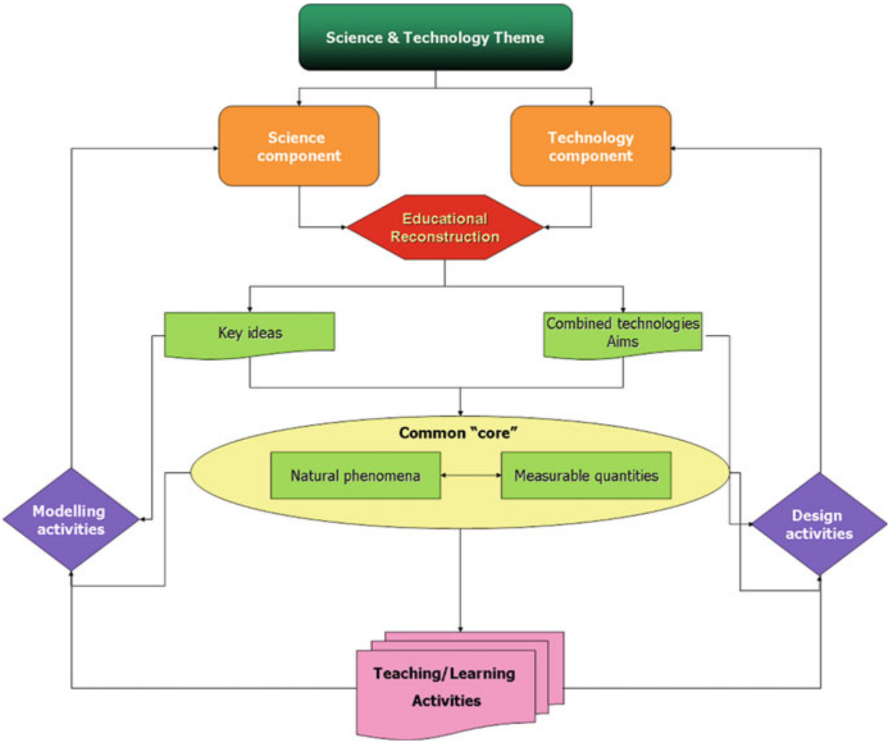

Fig. 4 Process of educational reconstruction to integrate Science and Technology

experiments useful to construct simple mathematical models. The process should be guided by the question of what could be considered as principal or secondary for the content to be reconstructed. For instance, if the aim is to construct a simple energetic model of the bouncing of ball on a floor, one may measure the subsequent maximum heights and concentrate the analysis on the floor's material and on the sound emitted during the hit, disregarding the effects of the air friction.

The same route can be followed to reduce the technological component into its basic technologies and to identify the physics of the natural phenomena harnessed. The two routes should converge into *common* enucleated core made up of experiments and measurable quantities to study and describe phenomenology which is relevant to the chosen contents. The process may also take advantage of scientific modelling and technological design activities carried out to exemplify the role of the measurable quantities in the scientific and technological components interplay.

Although for the theoretical viewpoint here discussed the reconstruction of the content in terms of key ideas, relevant natural phenomena, modelling and design processes as essential, a privileged role is not assigned to the ER model. The same outcomes, from the pedagogical viewpoint, could *in principle* be obtained through different approaches or frameworks.

However, the ER model provides a detailed coherent framework, widely validated and used in different contexts, from teacher education (van Dijk and Kattmann 2007) to informal learning in out-of schools experiences (Laherto 2013). It explicitly aims at the reconstruction of contents starting from the structure of the content itself, a dimension usually not emphasized in other research-based framework useful to design teaching interventions (Design-Based Research Collective 2003; Lijnse 1998). Given the relevant role of content structure in the adopted views of NOS and NOT, the ER model has been the most suitable choice.

6 Contextualizing the Science and Technology Integration in Teaching-Learning Sequences

In this section we will briefly discuss a possible implementation of the ER model for a successful Science and Technology integration in a TLS. As argued in the introductory paper (Psillos and Kariotoglou, this volume), the development of a TLS may lead to valuable research results in terms of understanding learning processes or validating theoretical models, and students' learning outcomes. We used the TLS dimension to investigate: (1) the validity of the theoretical framework adopted for the integration of Science and Technology; (2) the effectiveness of designed activities for students' learning of Science and Technology related concepts and views. In this section we focus on how a TLS may be designed using the framework. In the case study we will focus on the effectiveness of the TLS.

Basically, the first choice concerns a suitable *theme* which features both Science and Technology components. A theme should be wide enough to include Science and Technology considerations, but not too extended to be dispersive. A specific need or aim can be associated to this theme to emphasize the aim of the Technological component. This first step does not differ from previous proposals (e.g. Beven and Raudebaugh 2004).

At the second step, our approach diverges from previous ones: the chosen content should be reconstructed following the indication of the ER model. As pointed out in the previous paragraph, such reconstruction includes: identification of the key scientific ideas at the base of the Science component to be reconstructed; identification of the phenomenon at the basis of the technology component; investigation of this phenomenon and of any related relevant phenomenology; addressing of common alternative conceptions about the scientific contents relevant for the phenomenon; construction of suitable models of the observed phenomenology and design of the solution to meet the original need; evaluation of such solution and, if needed, investigation of further significant phenomenology to re-design the solution.

From what pointed out above, the choice of the specific theme to address, with its Science and Technology component, is essential. In our opinion, some content areas are more appropriate than others to foster a better integration process.

Materials science is one of these areas, together with others like biotechnologies, computer science and neurological imaging. Materials science is particularly appropriate since it is intrinsically interdisciplinary (covering aspects of physics, chemistry, engineering, etc), has a relevant technology component, and possesses a high potential impact on society (new materials and their applications are likely to figure strongly in any reasonable scenario of the technological future).[18] Moreover, learning about "materials" is being introduced in current science education reforms as a goal in itself (Cajas 2001, p. 723).

A relevant field of the Materials Science area to show the strict science/technology interaction is that of the macroscopic properties of materials. Students' alternative ideas and naïve reasoning related to this field have been previously addressed in Science Education research, especially those concerning the particulate nature of matter (Driver et al. 1985; Lee et al. 1993). Moreover, didactic proposals (Russell et al. 1991; Roth 1998) have addressed aims as: to distinguish between an object' s properties (e.g., geometry, colour) and the properties of the material(s) that constitute the object (physical, chemical, …); to improve students' understanding of the functional role of such properties for choosing suitable materials in order to complete a given design. One example to illustrate how contents related to properties of materials could be reconstructed by means of the ER analysis is extensively reported in a following chapter of this book, using optical properties of materials as main theme. Another brief example is reported in the Appendix.

7 Conclusions and Implications

In this paper we have tried to answer two research questions: What contents should be taught in approaches aimed at implementing an integration between Science and Technology? How should these contents be treated to achieve an effective integration? To this aim, we have proposed an integration of Science and Technology from the content knowledge perspective, building on relevant aspects of NOS and NOT. These aspects can be resumed as follows:

- Science knowledge, constituted by theories and models constantly validated through agreement with experience, has as main goal the analysis of natural phenomena purposefully investigated through carefully designed experiments and

[18] Materials Science addresses different but connected content areas. One is aimed at developing new materials for technological uses. This kind of research requires a basic knowledge of physics and chemistry, in particular about the macroscopic properties (known and desired) of materials (mainly solids) and the microscopic models explaining the known properties at the basis of studies toward the desired ones. The development of new organic materials is also being pursed in genetic engineering, bioengineering and biotechnology. In this case basic knowledge of biology and chemistry is needed, specifically concerning the macroscopic properties of biological systems and the microscopic models appropriate for the desired properties. In all these disciplines there is a link to technological applications and a common basic knowledge: the scientific description of macroscopic properties of materials and the microscopic models used to explain them. There are differences at the macroscopic and the microscopic level: for inorganic materials the properties are mainly physical and chemical; the models use atoms and subatomic particles as components. For organic materials biology comes in and the models use biological macromolecules or genes as components.

described, interpreted and predicted by theories and models, whose components are measurable quantities and their relationships;

- Technological knowledge has as main goal to solve specific problems through assembling practices and components and recombining existing technologies improved in small steps done by the selection of better solutions to design problems. Every technological object or device is a system characterized by a given aim and is built on several components, each itself is a technological object, which harnesses and/or exploits a natural phenomenon; the basic mechanism that allows to re-combine existing technological objects to obtain a new one is the technological design.

These aspects form the theoretical basis for the proposed integration of Science and Technology, since both at their very core rely respectively on investigating and exploiting natural phenomena. Therefore, to ensure this integration, the scientific and technological contents, which in the school curricula are separately finalized for the bodies of knowledge of Science and Technology, should be first elementerized and reconstructed until their core phenomenon is disclosed.

The ER model has been adopted to frame this process having in mind the broader aim of developing TLSs which effectively integrate Science and Technology. To answer specifically to the first research question, the model is applied in two examples (see Appendix) to show how specific themes can be elementerized. This implies to enucleate key ideas, to experimentally investigate relevant phenomenology and to describe it with suitable models. Some suggestions for design tasks to enrich the reconstruction of the technological contents are also discussed.

The following potentialities of the proposed approach can be highlighted from the SL perspective.

First, the approach overcomes some difficulties in STS, STSE and SSI instruction in dealing with Technology, as essential component of SL. In particular, the term “technology object or device” is used instead of technological “applications”, to stress the fact that every technological object is a combination of existing ones. In this view, the *human need* that Technology satisfies is important as well as the *phenomenon* and the *physics* that it exploits. As a consequence, the “technology as applied science” viewpoint fades away: namely, both Science and Technology rely on a common, educationally relevant to help students *become* and *act as* informed citizens.

Second, the envisaged reconstruction process, by identifying a common core as a part of Science or of Technology, addresses the issue of the quantitative integration of scientific and technological contents in previous approaches. In the teaching practice, it is then possible to focus mainly on the relationships (moral, economical, political, …) between the proposed themes and societal issues, diminishing possible resistances in introducing them in the school practice (Gayford 2002; Sadler et al. 2006) and helping students use meaningfully the acquired knowledge to decide on these issues (Sadler and Zeidler 2005b).

Third, the inclusion of design tasks into science teaching is strongly justified since technological design is an essential component of the proposed approach, with an analogous role to scientific modelling. Design tasks are hence not fashionable ways to improve science teaching, but tools to show recombination of existing technologies to obtain new ones.

A final consideration concerns some previously debated implications for Science and Technology teachers (Carlsen 1998; Barak and Pearlman-Avnion 1999). In particular, the proposed approach may help overcome usual difficulties teachers found in Science and Technology integrated proposals (reported by Barak and Pearlman-Avnion 1999; and by Geraedts et al. 2006). Actually, it does not add the two school subjects and does not demand teachers to look for difficult balance of contents. On the contrary, it fosters the teaching of common core contents and elicits some profound aspects of the nature of *each* of the two disciplines. Moreover, teachers are not asked to leave out traditional contents; if suitably reconstructed, they can be used as starting point to identify a Science and Technology common core. The Properties of Materials topics (Sect. 6) are further examples to introduce students to key concepts in Science and Technology.

Therefore the approach discussed in this paper can be valuable from the educational viewpoint provided that science and technology teachers become eager to address epistemological roots of and to bridge the existing gaps between the two subjects.[19] It is our convincement that when teachers become aware of the epistemological commonalities between Science and Technology, they, at least, are able to open up their school curricula "disciplinary boxes" (Carlsen 1998).

Appendix: Outline of an Example Which Uses Properties of Materials as Suitable Field to Integrate Science and Technology

Electrical Properties of Materials

Their educational relevance comes from the very many applications of electrical circuits in everyday life. They include electrical conductivity, dielectric strength and temperature coefficient of resistivity. A possible starting point is the study of the safety and comfort of cars (Science and Technology connected part) with the specific aim of reducing effects of mechanical vibrations (emphasized technological aim). The scientific component at its very core refers to the concept of potential difference at the ends of materials and how it depends on the system which the materials are part of. The technological component consists in the electronic device present in every modern car that controls and monitors the external vibrations.

[19] For instance, in Italian secondary schools, Physics teachers in Lyceums usually focus more on conceptual knowledge, while Electronics teachers in technical/vocational schools generally place more importance on laboratory practice.

Some key ideas suitable to reconstruct the potential difference concept are the density of charge or the energy and work per unit charge. The core phenomenon at the basis of the electronic device is piezoelectricity, an effect that allows the conversion of a mechanical stress into an electric voltage.

Once we have reached the common core content, it is possible to carry out investigations to measure potential differences across conductors or piezoelectric crystals, using electric cigarette lighters or portable sparkers. Finally, the teaching may address how to interpret and predict variations of potential difference at the ends of conductor materials as well as the design of a feedback device to control cars' vibrations focusing on the behaviour of materials exhibiting the piezoelectric effect.

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Part III
Case Studies

The Process of Iterative Development of a Teaching/Learning Sequence on Acoustic Properties of Materials

María I. Hernández and Roser Pintó

1 Introduction

Within the field of science education, several research-based instructional assignments and approaches for improving students' understanding of scientific knowledge have been developed over recent decades (Méheut and Psillos 2004). Furthermore, sound theoretical frameworks and methodological tools have been elaborated to guide the design and validation of teaching/learning sequences (TLS), e.g., Didactical Structures (Lijnse 1995), Learning Demands (Leach and Scott 2002), Teaching Experiments (Komorek and Duit 2004) and Model of Educational Reconstruction (Duit et al. 2005). The main aim of all these approaches consists of "reducing the uncertainty of decision making in designing and evaluating educational interventions" (van den Akker 1999, p. 5).

Like many other researchers in the field of science education, when we begin a research study, we are guided by diverse aims such as the applicability and efficacy of its results in particular classroom contexts or the attention to the changing needs that teachers face when a new syllabus or reform policy is introduced. In addition, when we decide to elaborate an innovation based on research results (e.g., a TLS) that fulfils those requirements, we also intend to contribute to the existing theoretical and methodological frameworks. These are some of the main reasons to initiate and conduct design-based research.[1]

One of the most common agreements among most of the different approaches to design-based research (Lijnse 1995; Design-Based Research Collective 2003) is the

[1] We adopt this term in a broad sense to refer to various kinds of research approaches that are related to design, development and evaluation of educational interventions, programs, processes and products (design research, development/developmental research, etc).

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fact that the development process of any innovative intervention should be iterative or cyclical, as it involves different stages such as design, implementation, analysis, evaluation and redesign, enlightened by research data, in order to achieve an appropriate balance between intended learning objectives and learning outcomes. We agree with van den Akker (1999, p. 9) when he stated that "direct application of [pedagogical] theory is not sufficient to solve many complicated practical problems, so an iterative process of 'successive approximation' or 'evolutionary prototyping' of the 'ideal' intervention is desirable." Lijnse and Klaassen (2004, p. 538) also argued that "the application of general (learning) theories results in heuristic rules that simply cannot guarantee that the teaching process that is supposed to be governed by them will have the necessary didactical quality." We agree with these authors about the need to search for evidence of good ways of teaching a certain topic and to discuss the didactical quality of an innovation (e.g., an innovative TLS dealing both in content and pedagogical approach).

Although several publications have reported the design and evaluation of an innovative TLS on a certain topic, not many empirical studies have reported relevant details of the process of refinement of a TLS analyzing the different changes that this development process entails and thus suggesting further ways to overcome the identified weak points or flaws of the designed sequence. Our perspective is that more in-depth research studies are necessary to provide compelling insight into how to refine a sequence so that this process is not undertaken via intuition but is based on research results.

With the intention of contributing to an understanding of these issues, we have carried out a research study describing, analyzing and interpreting the process of iterative development of a TLS on acoustic properties of materials (APM).

2 Context

The design and development of a TLS on APM were carried out during three consecutive years (2007–2009) by three researchers in science education and six experienced secondary school teachers (one physics graduate and five chemistry graduates) from four different schools. The researchers and teachers collaborated actively as part of a community of practice (Wenger 1998), called a "local working group" (LWG), while engaged in the design of educational materials.

Most of the secondary school teachers who engaged in the group had certain previous experience in educational materials development, and some of them are enrolled in continuous professional development courses. The main reasons to opt for strong university–school collaboration for the development of the sequence were the focus on learning on the part of all the members of the community of practice (see Chapter 5) and the intention to avoid critical transformations of the innovation when implementing it. Relevant studies (Pintó 2005; Viennot et al. 2005) have actually shown that a passive role on the part of teachers when designing an innovation might have deep implications for its implementation, often leading to a distortion of its rationale in a critical way.

The local working group evolved during the three years not only as regards the expertise of the members but also as regards the number of people, since new secondary school teachers who were colleagues of the previous teachers decided to become part of the group at some stage of the process of development of the TLS.

During the design of the TLS, all the members of the established LWG collaborated actively in periodic face-to-face meetings and by means of an online platform. In an initial stage, a preliminary content structure for the sequence was decided among the LWG members. The role of the researchers consisted of (1) guaranteeing that the specific learning targets[2] that each task pursues are explicit, (2) carrying out the didactical transposition of the contents and (3) suggesting the didactical approach to be introduced in the material (mainly the model-based inquiry approach) and the experimental setting. These three goals were quite innovative for the teachers involved in the LWG. Nevertheless, any decision was discussed and agreed upon with the teachers during the LWG meetings with the purpose of promoting teachers' sense of ownership of the innovation (Ogborn 2002). During these meetings, the teachers also provided useful remarks aboutstudents' skills, background and real classroom contexts, which allowed adapting the guidance for students. In short, teachers and researchers worked together at the core of designing the assignments and the assessment tasks of the teaching sequence (Pintó et al. 2009). During the refinement of the TLS, all the members of the LWG also collaborated in discussing possible flaws of the material and suggesting changes to refine the first version of the material.

The designed TLS on APM was planned to be implemented in ordinary schools with tenth graders (15- to 16-year-old students) within the science subject "physics and chemistry." In the Spanish educational context, tenth grade is the last compulsory academic year for students under 16 years old and it is also the first grade in which the study of physics and chemistry is optional. The official science syllabus in our context for the last year of compulsory secondary school, which suggests a qualitative and phenomenological study of the contents, includes the following main topics: sound waves and structure and properties of matter, among other topics. Each of these topics includes a number of subtopics detailed in Table 1.

Most of the aforementioned subtopics of sound and properties of matter were studied before the implementation of the innovative sequence on APM as prerequisites for it.

Nevertheless, this sequence represented an innovation for the teachers involved in the design and implementation of the sequence since it integrates the aforementioned topics in the study of the acoustic behavior of materials related to their properties and internal structure. Moreover, the sequence also meant a challenge for the teachers with regard to the didactical approach. Although all the teachers in our

[2] These are expressed in a very specific and measurable format, and the attainment of them can be determined within a given sequence or lesson. These are usually formulated: "Students are expected to be able…".

Table 1 Description of some topics included in the Catalan official science syllabus

Topic	Subtopics
Sound waves	Characteristics of sound waves, propagation of sound waves, phenomena related to sound such as reflection, sound production, hearing
Structure and properties of matter	Particulate nature of matter, atomic structure, atoms and molecules, relationship between properties and structure of materials

context are used to encouraging students to work in groups to a greater or lesser extent, most of them were interested in learning different teaching strategies to promote more effective engagement and learning in students. The experimental tasks proposed in the sequence meant a minor challenge for teachers and students since all of them are familiar with the use of data capture systems and related software although the specific sensor that was used (sound level meter) represented a novelty for them.

The local educational culture facilitated the development and introduction of these innovations since teachers are constantly encouraged by professional development programs or other organizational structures to experiment with different teaching strategies and to use a variety of materials and resources. Furthermore, teachers have autonomy to introduce the changes that they consider necessary in their classes.

3 Design of a Teaching/Learning Sequence on Acoustic Properties of Materials

3.1 Theoretical Framework for the Design of the Sequence

3.1.1 Elicitation of Design Principles

As Kali et al. (2009) stated, curriculum development is based on the epistemological views of the designers. Designers make epistemological assumptions about the nature of knowledge in a specific scientific domain and about how learning takes place, which stem from theories or perspectives on learning. Several epistemological assumptions were discussed and taken into account when designing conditions to promote students' learning with understanding of the topic of acoustic properties of materials. Hereafter, the explicit guidelines based on theoretical assumptions and empirical arguments that were used to orient the design of the TLS on APM are called design principles.

With the purpose of informing the design of the TLS on APM, we drew on the Two Worlds framework, stated by Buty et al. (2004). The epistemological hypothesis underpinning this framework is that modeling processes play a central part in understanding science by relating descriptions of objects and events in the material world to the world of theories and models. Everyday knowledge and scientific knowledge offer ideas and languages for describing objects and events of the material world; these are linked via modeling processes to distinctive theories and models for interpreting, predicting or explaining events in the material world. As stated by Tiberghien, "the distinction between the world of theories/models and the world of objects/events serves to make explicit the modelling processes that establish relationships between them" (Ruthven et al. 2009, p. 335). Drawing upon the Two Worlds framework, the TLS on APM was designed to help students move from descriptions of objects and events towards explanations in terms of models and theories, from everyday knowledge towards the perspective taken by science. Thus, modeling is considered a key scientific practice, and hence, the designed sequence is intended to promote students' engagement in their own process of development of coherent conceptual models.[3]

This emphasis on modeling is mediated by an inquiry approach so that the designed sequence proposes not only that students elicit, build, use, compare, evaluate and refine conceptual models but also that they ask questions, reflect on, design and perform experiments and strategies to solve particular problems. This approach, called the model-based inquiry by Windschitl et al. (2008), is grounded on the idea that "the particular practices that are integral to the core work of science are organized around the development of evidence-based explanations of the way the natural world works" (p. 943). Accordingly, the scientific practices promoted in the designed sequence do not merely refer to simple manipulative tasks but they also involve thinking/reasoning strategies, which can be complex and demanding for many students. For this reason, providing students with gradual scaffolding throughout the activities of the sequence, depending on how familiar students are with certain practices, tools or contents, becomes necessary to support students' modeling and development of inquiry skills.

On the other hand, the TLS on APM was drawn upon a problem-posing approach, providing students with a series of key questions contextualized around a certain scenario (soundproofing and acoustic treatment of a disco). According to Lijnse (2005), the emphasis of a problem-posing approach is not merely on engaging students in the process of solving a certain problem but rather on experiencing a content-related sense of purpose and on coming to see the point of developing their existing conceptual knowledge and experiences. In this sense, some of the questions of the sequence are oriented to make students reflect on why they are doing each task and where each task should be leading them (i.e., to promote students' metacognition).

Another design principle relating to the structure of the TLS was taken into account. The TLS on APM is constituted by multiple types of activities, and the sequence of activities is organized, taking into account the purpose of each activity

[3] Generally, a conceptual model is understood as an external representation of real objects, phenomena or situations shared by a given community (researchers, teachers, engineers, etc) and coherent with scientifically accepted knowledge that facilitates the comprehension or the teaching of systems or states of affairs in the world and that results in a powerful explicative and predictive tool for the interaction of subjects with the world (Greca and Moreira 2000).

and the stage of the learning cycle in which the activity is implemented. Thus, the sequence of instruction involves the following phases:

1. Engagement of students and eliciting of students' previous ideas: discussion from key questions or posed problems, justification of certain statements and/or predictions using preliminary models, etc.
2. Introduction of new concepts or procedures: observation, design and realization of experiments using MBL technology, discussion from key questions or posed problems, interpretation of experimental results and/or graphs, use of analogies, etc.
3. Structuring one's own knowledge: contrast of different perspectives, elaboration of explanations, reflection on one's own conclusions, etc.
4. Application of the developed knowledge: application of the conceptual models in different situations, use of procedural knowledge in designing and performing experiments to carry out an investigation.

Regarding classroom management, most of the aforementioned tasks were undertaken in small groups of students. A balance between assignments in small groups and whole class discussions was also promoted so that teachers and students provided feedback for formative assessment.

In short, several design principles informed the TLS on APM and oriented the pedagogical approach of the material, the teaching strategies and the organization of the teaching and learning activities.

3.1.2 Subject Matter Clarification and Analysis of Students' Learning Needs

According to the Model of Educational Reconstruction (Duit et al. 2005), a good design process also requires sensitivity to students' learning needs and to reconsider (or "reconstruct") the scientific content to be taught from an educational perspective.

Taking this perspective into account, the design of the sequence on APM involved several stages addressed to critically analyze the subject matter and the educational significance of the topic for 15- to 16-year-old students. Thus, the design of the sequence comprised the following three phases:

- Analysis of the subject matter and its technological applications, based on several publications on the topic coming from different fields: acoustics, engineering, architecture, physics and materials science.
- Review of previous research studies about students' conceptions of the nature and propagation of sound.
- Preliminary research study about 15- to 18-year-old students' conceptions on sound attenuation and acoustic properties of materials.

3.1.2.1 Analysis of the Subject Matter

Sound is a classic area of physics present in most science syllabuses. Linking sound with the important everyday idea of noise pollution is also common in syllabuses with an STS (Science-Technology-Society) or contextualized approach. Understanding noise pollution needs to be accompanied by a real understanding of how sound propagates and how sound is attenuated. For the design of the TLS on APM, we took into account these elements (noise pollution, sound propagation and sound attenuation) but we also focused on some technological aspects (applications) in our attempt to introduce ideas of materials science. Accordingly, the designed TLS on APM is focused on analyzing the relationship between properties and internal structure of specific materials in order to account for their acoustic behavior, that is, the way materials behave in front of sound regarding attenuation. The approach to the study of sound and acoustics in combination with materials means an innovative and challenging approach in our educational context since we have no evidence of the existence of any previous didactical transposition[4] on this topic for secondary school students.

Different specialized sources such as web sites, doctoral dissertations (Ruiz 2005; Juliá 2008) and books (Long 1980; Recuero 2000; Rossing 2007) were used on the topic of sound attenuation and acoustic properties of materials in depth.

The consulted bibliography generally presents sound attenuation as the combined effect of scattering and absorption produced by materials, which weakens sound further than the mere propagation of sound when it spreads through a medium. The designed sequence does not distinguish between scattering and reflection of sound but emphasizes reflection as one of the mechanisms of sound attenuation when sound reaches an interface between two mediums. Absorption is understood as the energy dissipation of sound waves within a single medium. From this perspective, two types of sound attenuating materials are distinguished depending on the mechanism of sound attenuation that predominates: sound reflectors and sound absorbers.

Nevertheless, in such consulted literature, sound attenuation is often not of intrinsic interest as a phenomenon. Rather, most of the sources mainly focus on the acoustic properties of materials and other variables that affect sound attenuation (e.g., frequency of the emitted sound, shape of the surface of objects and thickness of material plates, etc). Understanding the variables that affect sound attenuation is the first step to be able to control these variables when designing and selecting appropriate materials for soundproofing (avoiding sound coming from or going outside a room) and acoustic treatment (adjustment of sound reverberation).

Concerning the interaction between sound and materials, one common magnitude that is generally mentioned as related to properties of materials that affect

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[4] The didactical transposition consists of the migration of knowledge from the community of reference, called the reference knowledge, towards the knowledge to be taught (Chevallard 1991). In our case, the reference knowledge is the scientific knowledge whereas the knowledge to be taught can be found in the community of teachers and researchers in the form of the designed TLS.

sound transmission is the acoustic impedance (*Z*) of a material, defined as the product of its density (ρ) and acoustic velocity (v):

$$Z = \rho \cdot v$$

Since acoustic velocity or speed of sound propagation through a certain material medium is generally defined as:

$$v = \sqrt{\frac{k}{\rho}} \quad (k \text{ being the elastic modulus}),$$

then the acoustic impedance could be redefined as:

$$Z = \sqrt{\rho \cdot k}.$$

This last equation summarizes the dependence of the acoustic impedance upon two essential types of properties of the material medium through which the sound wave is traveling: elastic and inertial properties. In our didactical transposition, these properties are considered as follows:

- Elastic properties are those properties related to the tendency of a material to maintain its shape and not deform whenever a force or stress is applied to it. At the microscopic level, a very elastic material is characterized by atoms and/or molecules with strong attractions among each other. When force is applied in an attempt to deform the material, the interactions among its particles prevent the deformation and help the material maintain its shape. The designed sequence characterizes materials according to their elasticity, distinguishing rigid materials (high elasticity or high elastic modulus k) from flexible materials (low elasticity or low elastic modulus k).
- Inertial properties are those properties related to the object's tendency to change its state of motion. The density of a material (ρ) is the magnitude related to the inertial property. At a microscopic level, density is related to mass of the particles that form a material and to packing of these particles. The designed sequence depicts density of solid materials as related to the inertia or mass of their particles (considering equal volumes). According to this view, the greater the inertia of the particles of a medium, the less responsive they will be to the interactions between neighbouring particles.

Acoustic impedance is therefore a magnitude that plays a relevant role in determining sound transmission and reflection at the boundary between two mediums that have different acoustic impedance. In fact, sound reflection only occurs when sound reaches the interface between two materials with different acoustic impedances. The difference in acoustic impedance is commonly referred to in specialized bibliography as the impedance mismatch. The greater the impedance mismatch, the greater the percentage of energy that will be reflected at the boundary between two mediums. Rephrasing the idea of impedance mismatch in our didactical transposition, we can consider that the greater the difference between density and elasticity of two mediums, the greater the percentage of energy that will be reflected and the lesser the percentage of energy that will be transferred to the material when sound reaches the interface. Therefore, very elastic and dense materials usually behave as good sound reflectors to attenuate sound that propagates through the air. On the contrary, sound absorbers behave as bad sound reflectors and, therefore, are usually less elastic and dense.

While acoustic impedance is a magnitude useful in explaining the distribution of energy that is reflected towards the same medium or is transferred to another material when sound reaches an interface between two mediums, it does not account for how sound is absorbed within a certain material. Apart from density and elasticity, which actually affect the acoustic behavior of materials, the effect of porosity is also recognized as a property of materials that affects sound absorption. When sound reaches a porous material, it is mainly absorbed. In our qualitative description of the phenomena, this effect can be explained in terms of the friction between the air inside the material (within the pores, between fibers) and the solid walls (or skeleton) of the material. Moreover, when sound propagates within a porous material, it is reflected many times because there are several air-solid-air interfaces. Due to friction and to the multiple reflections within the pores, part of the energy associated with sound is transferred to the solid skeleton of the material, by making its particles vibrate, and therefore, it is dissipated. In summary, porous materials usually behave as good sound absorbers but bad sound reflectors.

The soundproofing of a real room or precinct, as the consulted specialized and technical literature describes, would need to take into account other factors that play a role in sound attenuation, such as the frequency of the emitted sound, the shape of the surface of an object, the thickness of the plates of material, among other things. However, the level of the students to whom the designed sequence was addressed and the complexity of the topic were considered as strong reasons to limit the sequence to the study of properties of materials that affect their acoustic behavior. These paragraphs summarize the main ideas resulting from the didactical transposition carried out for teaching about sound attenuation (sound reflection and absorption) and about the properties and internal structure of materials that play a role in their acoustic behavior (density, elasticity and porosity).

3.1.2.2 Review of Previous Research on Students' Conceptions of Sound

Identifying the preconceptions that influence students' understanding of sound phenomena was a central step in designing the TLS on APM. Several previous studies carried out during the last two decades have focused on students' representations and common preconceptions of sound, before or after a formal instruction. The main findings of these studies could be summarized as follows:

Students' Conceptions of the Nature and Propagation of Sound

The most common result obtained from several research studies intended to analyze students' preconceptions of the nature of sound is the evidence of a mechanistic spontaneous reasoning or mental model, often named "entity model" of sound. This model can be characterized in terms of the following attributes:

- Sound signals are conceptualized as material objects created and set in motion by the source.
- Sound is considered an entity which is transported by individual molecules (*sound particles*), which move along a medium.
- Sound is considered an entity which is transferred from one molecule to another molecule of a medium but is different from the medium where it propagates.
- Sound is considered a limited substance which travels with a certain impetus and is generally represented as an air current.
- Sound is considered a substance which travels following the pattern of waves.

This kind of spontaneous reasoning has been evidenced in elementary school students (Mazens and Lautrey 2003), as well as in secondary school students (Maurines 1993; Eshach and Schwartz 2006) and undergraduate physics students (Linder 1992; Hrepic et al. 2010; Wittmann et al. 2003).

Students' Conceptions of the Interaction of Sound with Matter

Some research studies (Linder 1993; Maurines 1993) also analyzed students' explanations of the factors that affect the speed of sound and the interaction of sound with a certain medium. The main findings are as follows:

- Molecules of a medium are conceptualized as an obstacle to the propagation of sound through the medium.
- The speed of sound is conceived as dependent on the source or the signal amplitude but independent of the properties of the medium.
- Even recognizing that speed of sound depends on density and elasticity of materials, density is often conceptualized as related to the distance between the molecules of a medium and elasticity is conceptualized in terms of compressibility and as inversely proportional to density.
- Sound can propagate through the vacuum and can be transmitted through the empty spaces between the particles that form a medium.

In short, these research studies evidence that previous knowledge of students in any educational level tends to be materialistic or "based in substances." This implies that students tend to attribute properties or behaviors of material substances to abstract concepts as in the case of sound, which is ontologically conceived by science as a process or event rather than an entity.

3.1.2.3 Preliminary Research Study on Students' Conceptions of Sound Attenuation and Acoustic Properties of Materials

Although many aspects and attributes of the so-called entity model of sound had been described and reported by several authors, we did not find any study devoted to the analysis of students' conceptions of the specific topics we wanted to address in the TLS on APM – mechanisms of sound attenuation and acoustic properties of materials. For this reason, we decided to specifically explore 15- to 18-year-old students' ideas on this topic. The sample of this preliminary study (Hernández et al. 2012) was formed by 76 upper secondary school students, who were administered a questionnaire containing a question that asked them to explain why some materials attenuate sound more than other materials. The questionnaire was administered after having performed an experiment in which students had measured sound transmitted through different materials to determine the best sound insulator. Analyzing students' answers, we interpreted the properties of materials that the students consider affect their acoustic behavior and the students' understanding of the phenomenon of sound attenuation. The findings of this study can be summarized as follows:

Students' Conceptions of the Phenomenon of Sound Attenuation

About half of the students (40/76, 53 %) explained some mechanisms of sound attenuation. The rest of them did not explain what they understood by sound attenuation but mentioned certain properties of materials that might affect their acoustic behavior to explain differences of sound attenuation caused by different materials. From the answers of the students who explained some mechanisms of sound attenuation, we could evidence some preconceptions:

- Most of them (15/40, 38 %) considered that sound insulators behave as sound barriers that prevent the passage of sound. This kind of conceptualization might imply an underlying idea of sound as a physical entity that can or cannot go through a material depending on certain characteristics of the material, such as porosity. This conception was labeled "sound attenuation by hindering the entrance of sound."
- Some students (5/40, 13 %) conceptualized sound attenuation through a material as the decrease of the speed of sound within the material. Therefore, these students consider that the speed of sound is not constant through a uniform medium but decreases while sound propagates through it. This conception was labeled "sound attenuation by slowing down sound."
- Some students (6/40, 15 %) also recognized sound absorption as a phenomenon that accounts for sound attenuation even though they did not give any explanation of absorption in terms of energy dissipation. In many cases, the students who explained sound attenuation as the absorption within a material evidenced a materialistic reasoning in terms of the "entity model" of sound. This conception was labeled "sound attenuation by capturing sound."

Students' Conceptions of Acoustic Properties of Materials

Most of the students (64/76, 84 %) responded to the questionnaire mentioning different properties that might influence the acoustic behavior of materials. Analysis of their answers evidenced, to some extent, that the students' conceptions of sound and sound attenuation are closely related to the properties that they associate with the acoustic behavior of materials. Nevertheless, as stated above, some students' conceptions of sound and sound attenuation are inconsistent with the scientific perspective and so are their conceptions of acoustic properties of materials. As an example, some students who express the idea that sound insulators are denser and non-porous also conceptualized sound attenuation through a material as the obstruction of the passage of sound.

Furthermore, students' conceptualizations of specific properties of materials at the level of their microstructure also tend to be oversimplified in some cases. As Linder (1993) already reported, many students consider that density of materials uniquely depends on the distance between its particles.

Considering the differences between the content to be taught and the students' conceptualizations of this content, the learning demands[5] for 15- to 16-year-old students and for the topic addressed in the designed sequence were identified. These learning demands can be summarized as follows:

- Students' understanding of the nature and propagation of sound needs to become more coherent with the scientific view. This means conceiving sound as an event or process instead of as an entity.
- Students' preconceptions of sound attenuation need to be refined according to the scientific perspective. This refinement or change means conceiving sound attenuation as a process of energy dissipation that involves reflection and absorption rather than an effect caused by materials when "hindering the entrance of sound," "slowing down sound" or "capturing sound."
- Students' conceptualization of the acoustic properties of materials (density, elasticity and porosity), at both macroscopic and microscopic levels, needs to become more coherent with the scientific perspective. For instance, this would imply considering density of solid materials as related to the mass of their particles instead of associating it to the distance between particles.

The identification of these learning demands was useful to formulate both the specific prerequisites and learning objectives of the TLS on APM.

[5]The learning demands for a particular conceptual area of science are considered as the gap between everyday and school science perspectives (Leach and Scott 2002).

3.2 *The Sequence of Teaching and Learning Activities as a Product of the Design Process*

As a result of the design process, a TLS on APM was obtained. The structure of the designed sequence and the main learning targets of this sequence are summarized in Table 2.

Table 2 Structure of the TLS on APM and intended learning targets

Unit	Learning targets	Activities
1. ***Sound-material interaction***	The global aim is to develop a conceptual model of sound attenuation in terms of energy. This aim can be specified in terms of the following learning targets:	**1. 1 Acoustic problems of a disco**
	LT1.1 To describe sound attenuation as the decrease of sound intensity level, associating this decrease to the difference between emitted sound and transmitted sound	Exploration and discussion of the context of the sequence and the problem to be solved
	LT1.2 To measure the sound attenuated through obstacles using a sound level meter	Eliciting of preliminary conceptions of sound propagation through different mediums
	LT1.3 To identify the phenomena involved in sound attenuation through materials (reflection and absorption)	**1.2 Why can sound reach any corner of the dance floor?**
	LT1.4 To distinguish sound insulators according to their acoustic behavior (sound reflectors and sound absorbers)	Eliciting of preliminary conceptions of sound reflection and reverberation
	LT1.5 To explain and to represent (with diagrams) sound attenuation as a process of energy dissipation, identifying some mechanisms of dissipation such as friction or dispersion	Exploration and interpretation of data, graphs and images to draw conclusions on sound reflection and reverberation
		Application of the refined conceptions in other activities
		1.3 How can we manage to avoid hearing too much sound outside the disco?
		Eliciting of preliminary conceptions of sound attenuation
		Introduction of the scientific point of view regarding sound attenuation

(continued)

Table 2 (continued)

Unit	Learning targets	Activities
		Interpretation of the acoustic behavior of two materials (sound reflector and sound absorber) using two diagrams that represent the distribution of energy (reflected, absorbed, transmitted) of an incident sound caused by each type of material
		Design and realization of an experiment to determine, using a sound level meter, how much sound is attenuated by a certain material
		Structuring of ideas in answering a question about soundproofing.
2. ***Properties and internal structure of sound reflectors and sound absorbers***	The main aim is to develop as follows:	**2.1 Which characteristics does a good sound reflector have? And a good sound absorber?**
	A conceptual model of sound reflectors and absorbers in terms of the physical properties that affect their acoustic behavior	Eliciting of preliminary ideas on the physical properties and internal structure of sound reflectors and sound absorbers
	A conceptual model of sound reflectors and absorbers in terms of their internal structure	Prediction of the acoustic behavior of several materials on the basis of their properties
	These aims can be specified in terms of the following learning targets:	Design and realization of an experiment[a] to determine if each of the previous materials behaves as a sound reflector or as a sound absorber
	LT2.1 To determine the acoustic behavior of materials (sound reflectors and sound absorbers) measuring/analyzing the levels of sound intensity	Classification of the tested materials in sound reflectors and sound absorbers on the basis of the empirical results
	LT2.2 To predict and explain how sound is attenuated (by reflection or absorption) when it reaches a material in terms of its acoustic properties (density, rigidity, porosity)	Description of the physical properties of the tested materials on the basis of their observations
	LT2.3 To distinguish the acoustic properties of materials and the characteristics of objects made of these materials that might affect their acoustic behavior	Identification of the physical properties that all the tested sound reflectors have in common (and the ones that all the tested sound absorbers have in common)

(continued)

Table 2 (continued)

Unit	Learning targets	Activities
	LT2.4 To represent density, rigidity and porosity of materials in terms of their microstructure	Application of the conceptual model in predicting the acoustic behavior of some materials in terms of their physical properties
	LT2.5 To predict and explain the role that certain properties play in influencing the capacity of materials of attenuating sound according to their microstructure	**2.2 How can we explain that the properties of a material affect its acoustic behavior?**
		Explanation of how sound reflectors and sound absorbers are internally configured using an analogy[b]
		Interpretation of mechanisms of sound attenuation in materials according to their internal structure
		Application of the conceptual model to explain why certain property of some materials affect their capacity of sound attenuation
3. ***Acoustic treatment and soundproofing***	The aim is to apply the previous conceptual models to design and perform a more open inquiry	**3.1 Comparing materials. Which one could be used to soundproof?**
		Engagement in a decision-making process to solve the original problem of the disco. The decisions, which are concerned with the selection of the most appropriate materials to soundproof and acoustically treat different areas of the disco, are to be based on pieces of evidence and models.

[a]This experiment consists of using a sound level meter to measure the sound intensity level produced by a sound source (e.g., a buzzer) that has been placed inside a cardboard box whose walls have been covered with a certain material. The box represents the structure of a room or closed space where there is a sound source, and the material that covers the walls represents the material used to soundproof that room. This measurement is compared with the reference value, measured when the box is not covered with any material. If the sound intensity level measured within the box covered with a material is higher than the reference value, then we can conclude that the material behaves as a sound reflector. If the measured value is lower than the reference value, we can conclude that the material behaves as a sound absorber. For more details about the experiment, see Hernández et al. (2011).

[b]The analogy is related to the mass-and-spring model of matter, and it compares particles that form each medium or material with pool balls connected by means of springs. According to this analogy, density is related to the mass of the balls and rigidity is related to the elastic constant of the springs connecting the balls. Porosity is related to the presence of air particles inside the pores of a material, which in turn is formed by different particles.

The designed sequence on APM is therefore intended to promote certain learning targets, such as coherent conceptual understanding of the conceptual models. Furthermore, the designed sequence is intended to contribute to students' development of inquiry skills, such as observation, measurement, classification, making inferences and predictions, problem-solving, controlling variables, interpreting data, etc. Metacognition is also one of the thinking skills that are fostered in the sequence, by means of questions specifically aimed at making students reflect on what they are learning. Nevertheless, these aims have not been formulated as learning targets in Table 2 since they are developed not only throughout this TLS but also throughout the whole science course, and so they are not explicitly assessed at the end of the implementation of the designed sequence. Finally, the whole sequence also serves some social purposes, such as to make students be aware of the problem of noise pollution and to emphasize the need for soundproofing of noisy places.

4 Development and Refinement of the Sequence

The design of the first version of the sequence was completed after having decided the students' learning targets, the activities and the procedures to evaluate the sequence. At this point, we tackled the issue of what indicators are more relevant to appraise the quality, success or impact of the innovation. As van den Akker (1999, p. 10) said, "quality is an abstract concept that requires specification." During a design process, the emphasis in criteria for quality usually shifts from validity to practicality (or usability), to effectiveness (or efficacy).[6]

After the first implementation of the designed sequence in different schools, the members of the LWG proceeded to evaluate the quality of the designed sequence taking into account the coherence between the designed sequence and the design principles, the teachers' perceptions of the implementation of the sequence and the students' performance during the implementation of the sequence. This chapter reports the evaluation of the quality of the sequence, conducting an in-depth analysis of the role of each designed activity, at a fine granularity level (Tiberghien et al. 2009).

The evaluation of the validity, practicality and efficacy of the sequence resulted in a refinement of the sequence. As a result of this stage of development of the sequence, a second version was obtained and implemented in the classroom. After this second classroom implementation, teachers and researchers evaluated the redesigned sequence on the basis of the new evidence obtained. The third version of the

[6] Validity refers to the extent that the design of the intervention is based on state-of-the-art knowledge (content validity) and that various components of the intervention are consistently linked to each other (construct validity) and can adequately be evaluated through expert appraisal. Practicality refers to the extent that users (and other experts) consider the intervention as appealing and usable in "normal" conditions. Effectiveness refers to the extent that the experiences and outcomes from the intervention are consistent with the intended objectives.

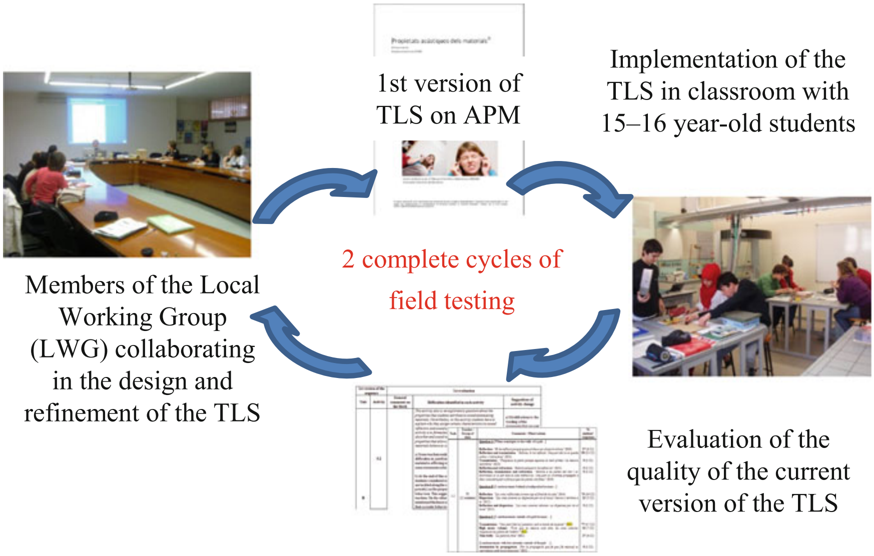


Fig. 1 Iterative development of the TLS on APM carried out by our LWG

sequence, resulting from this second evaluation, was developed and implemented again in different classrooms. The whole process is illustrated in Fig. 1.

5 Implementation(s) of the Sequence

The teachers who participated in the design of the TLS also committed themselves to implement the sequence in their science classes. Some of the teachers who participated in the first classroom implementation trial of the sequence also implemented the second and third versions of the sequence. Moreover, other teachers who did not participate in the design process but were colleagues of some of the previous teachers also joined the LWG and implemented the second and third versions of the sequence in their science lessons.

The teachers involved in the LWG implemented the sequence within the course of their own science classes and with their students. In other words, the conditions under which the sequence was implemented correspond to the ordinary context of their classrooms. Some noticeable differences in practice are as follows: (1) the teachers involved in the implementation of the sequence had different teaching styles and managed students' autonomy and collaborative tasks differently: some teachers were used to teaching by asking questions while others were more used to teaching by telling; (2) not all the teachers implemented the whole sequence, and therefore, they devoted different numbers of hours to the implementation; and (3) teachers could not implement the sequence at exactly the same academic level but at closer ones (ninth to eleventh grades).

Table 3 General description of sample

School	Description of the school	Number of students		
		First classroom trial	Second classroom trial	Third classroom trial
A	Unique state secondary school in a small town between bigger cities	22	14	–
	Mixture of socioeconomic background of students			
	Low number of immigrant students			
B	State secondary school in an urban area	14	–	12
	Medium-high socioeconomic background of students			
	Low number of immigrant students			
C	Privately run school funded by the state in a small town	29	16	17
	Medium-high socioeconomic background of students			
	Low number of immigrant students			
A + B + C	**Total sample**	**65**	**30**	**29**

For these reasons, and for the purposes of the research presented here, we reduced the sample to the class groups formed by 15- to 16-year-old students, who are the target of the designed sequence. Moreover, all the teachers who could implement the sequence at this level have some main features in common: (1) they implemented almost the whole sequence, devoting a similar number of hours (12–15 h) and following the written teaching and learning material as it was structured, (2) they all proposed collaborative work and active discussion among their students to a greater or lesser extent, and (3) they implemented at least two different versions of the sequence. Table 3 presents a general description of each of the schools to which these class groups belong as well as the number of students who constitute our sample.

6 Research Questions and Methods

6.1 Research Questions/Aims

We do not aim only at designing and validating a particular innovation on a certain topic or at improving gradually the quality of the designed sequence refining it. Rather, the main aim of this research is to analyze different aspects of the process of iterative development of the innovative TLS on APM, in an attempt to make explicit some of the features of a process of iterative development of an innovation in science education. This essential aim is addressed by the following research questions:

1. *What problematic aspects of the innovative TLS are identified when evaluating and analyzing it after having been implemented in real classroom contexts with 15- to 16-year-old students?*
2. *What changes are introduced in the designed TLS aimed at overcoming the identified problematic aspects?*
3. *What "driving forces" or "critical reasons" are associated with the changes introduced in the designed TLS?*

6.2 Research Methodology

This study has used an interpretive qualitative approach to examine the basic structure of the event under study – the process of iterative development of a TLS on APM – and to generate a model of successful innovation through such work.

As the present study is framed within the design-based research paradigm, we used a range of mixed methods and techniques to analyze the intervention's outcomes and refine the sequence: observation, collection of standard learning tasks with scoring rubrics and other techniques for learning assessment. Assessment techniques are domain-specific, that is, specific to the content being taught and the goals, and so new instruments have been developed for collecting data in the domain of APM, covered by the designed TLS.

6.3 Data Collection

In order to analyze the process of iterative development of the designed sequence, we collected several data (Table 4) during and after the three classroom implementations carried out in consecutive school years. Nevertheless, the analysis of students' outcomes from the students' written answers in a common examination is reported elsewhere (Hernández et al. 2014).

6.4 Data Analysis

The first level of analysis of the collected data consisted of the identification of the students' needs or difficulties for each activity during the implementation of the sequence in order to infer problematic aspects of the sequence that had resulted in those students' needs or difficulties. After having identified problematic aspects of the sequence, a series of modifications were introduced in the designed TLS. The

Table 4 Collected data

Sources of data	Year 2007–2008	Year 2008–009	Year 2009–2010
(a) Students' written answers in a common examination	✓	✓	✓
(b) Students' written answers and productions in their booklets	✓	✓	✓
(c) Teachers' diaries describing their perceptions of the implementation process	✓	✓	×
(d) Researchers' field notes after classroom observation during the implementation of the sequence	✓	✓	✓
(e) External experts' reports after classroom observation during some sessions during the implementation of the sequence	✓	×	×
(f) Informal notes taken during the face-to-face meetings of the LWG devoted to refining the sequence (teachers' perceptions and difficulties perceived during the classroom implementation of the sequence)	✓	✓	×

Table 5 Instrument to summarize and thus evaluate each assignment of the designed sequence

# Version of the sequence (# implementation)		# Evaluation			
Assignment/task (booklet)	Aim of the task	Students' or teachers' needs or difficulties identified in each task	Problematic aspects of the sequence for each task	Changes introduced in the task	Driving forces
Assignment #	–	–	–	–	–

changes in the sequence were described in detail as well as the critical reasons or driving forces that promoted that change. Table 5 shows the instrument used to summarize the analysis of each assignment of the sequence.

As a second level of analysis, we proceeded to cross the results of the analysis of each assignment of the sequence in order to categorize the types of students' needs or difficulties, the types of problematic aspects of the sequence, the types of modifications introduced in the sequence and the driving forces associated with these changes. Once these categories were defined, we analyzed the relationships between the types of students' needs or difficulties and the types of changes introduced in the sequence in order to identify possible patterns of modification that would allow us to describe aspects of the refinement of the sequence.

Finally, as a third level of analysis, we evaluated the quality of the refinement of the sequence by comparing types and prevalence of students' difficulties throughout the consecutive versions of the sequence. This analysis consisted of the quantification of each type of difficulty evidenced and each type of change introduced after each implementation. The resulting quantities are not related to the total number of students who participated in each implementation. On the contrary, the quantities refer to the number of difficulties (or changes introduced in the sequence) of each type that were evidenced throughout the whole sequence (without considering the same difficulty more than once). This quantification allowed a graphical representation of the evolution of the persistence of certain students' difficulties from the implementation of one version to the next.

7 Results

7.1 On Students' Needs or Difficulties

7.1.1 Types of Students' Needs or Difficulties

The fine-grained analysis of the collected data allowed us to evidence 15- to 16-year-old students' needs and difficulties when implementing the consecutive versions of the designed TLS on APM. Table 6 summarizes the types of students' difficulties identified when analyzing the data collected during the classroom implementation of the first, second and third versions of the sequence.

7.1.1.1 Student's Needs or Difficulties Related to Metacognition

The students' difficulties related to metacognition (DM) refer to the familiar problem that several authors have previously reported as "*the problem of students not knowing the purpose(s) of what they are doing, even when they have been told*" (Gunstone 1992). The following answer from a student who participated in the implementation of the first version (V1) of the sequence is intended to exemplify this type of difficulty:

Table 6 Types of students' needs or difficulties identified during the implementation of the sequence

Category	Description
DM	**Related to metacognition**: Students do not identify the intended aim of a question/statement or do not challenge some of their own existing ideas although they are told to reflect on them critically
DI	**Related to images**: Students do not interpret appropriately the meaning of a visual representation, picture or graph related to a concept or phenomenon
DC	**Related to concepts or conceptual models**: Students do not use appropriately a conceptual model or do not attribute an appropriate meaning to a certain concept when predicting, interpreting or explaining phenomena
DE	**Related to experiments**: Students do not control the variables, do not evaluate the limitations of an experiment when designing and planning it, do not interpret appropriately the magnitude or values of the measurements they take with an instrument or do not analyze adequately the experimental data they collect
DO	**Related to other aspects**: Students are not familiar with the procedures of a certain kind of assignment or do not give a written answer in their booklets

After having measured the variation of the intensity level of a constant sound source as the distance between the source and the sensor (sound level meter) increases, students were asked:

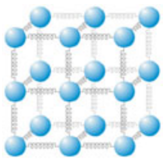
Question (V1): From the measurements obtained in the previous tests, which conclusions can you reach?

Student's answer: "*Our predictions [graphs] are quite similar to the real ones, but they would be more similar if there was not so much noise in the classroom*" (S01B)

The previous quote highlights that the student does not explain or interpret the experimental results in terms of the decrease of sound intensity level as the distance between the source and the sensor increases, as expected, but he/she slightly compares his/her own prediction with the obtained graph. Although the previous example of activity is not a metacognitive task since it does not ask students to make an explicit statement about the purpose of the question, we interpret that this answer plausibly evidences a lack of the student's awareness of the aim of the activity, and thus, we consider that the student's difficulty in this answer is related to metacognition. Other students' difficulties related to metacognition were evidenced in answers to metacognitive tasks, in which students were explicitly asked to reflect on their previous ideas, to compare them with different ones and to refine them.

7.1.1.2 Student's Needs or Difficulties Related to Images

Students having difficulties reading images (DI) is another common problem identified during the implementation of the sequence. Students' difficulties reading visual representations are in some cases associated with students' (lack of) understanding of the concepts represented in the image, but often they are also attributed to problematic features of the designed images and their accompanying verbal elements. The images that are part of the TLS were designed and introduced as a visual aid for students' understanding of processes or concepts. In this sense, the TLS is considered the *interpretative context* (Ametller and Pintó 2002) where images convey a certain meaning. Nevertheless, in some cases, such interpretative context seems not to be enough or adequate since we evidenced that some students did not interpret appropriately the meaning of the image (and its caption) or simply did not make any sense of it. Let the next quote serve as an example of this type of difficulty:



Model that relates the internal structure of a material and its rigidity (Molecules are represented by balls and bonds are represented by springs)

The ball-and-spring model and its corresponding caption were included with the purpose of contributing to the building of a conceptual model that relates the rigidity of materials to the strength of the bonds between its molecules. After having introduced the image and caption shown above, students were asked the following question:

Question (V1): Using the microscopic model of a material, explain how rigidity of a material affects the fact that the material reflects sound.
Student's answer: "*If a material is more rigid, the atoms are less prone to move and transmit sound because the springs are less deformable and the atoms vibrate less*" (S07B)

As the previous example illustrates, this student explains rigidity of a material at the level of its internal structure in terms of "springs" between atoms as represented in the image. Although the previous student's answer can be interpreted as a good explanation of sound transmission/attenuation in a material in terms of the vibration of its particles, we consider this answer problematic since it mixes elements from the source of the analogy (springs of the image and their property of "deformability") with elements from the target of the analogy described in the caption (atoms). Bonds do not appear in the answer but are substituted by springs. Thus, we interpret that the student's difficulty is related to the image used with the analogy. We consider that if the student had been able to integrate the information provided by the caption with the visual elements of the image, he/she might have been able to "decode" the analogy.

Other problems identified regarding images are concerned with the inadequate interpretation of graphs or of a collection of static images which represent a process or phenomenon.

7.1.1.3 Student's Needs or Difficulties Related to Concepts or Conceptual Models

The third type of students' difficulties evidenced in analyzing students' answers corresponds to the conceptual difficulties (DC). Let us note that for this analysis, we did not consider students' difficulties evidenced in eliciting their previous ideas, although some of these ideas might be inadequate. That is to say that what we report here as conceptual difficulties are those students' problematic conceptions or reasoning evidenced after the students' involvement in tasks and assignments that were devoted to promote students' understanding of a certain concept or conceptual model. Therefore, we only considered as students' difficulties those students' conceptions, different or similar to students' previous ideas, which are not consistent with the scientific perspective and have not been overcome throughout the sequence. Thus, these students' difficulties allow interpreting the weak points of the designed sequence. The following student's answer evidences some conceptual difficulties:

After having observed several porous materials (with the naked eye and with a binocular microscope), having been introduced to a verbal description of the internal structure of porous materials and having explained sound attenuation in terms of energy, students were asked the following question:

Question (V1): Using the microscopic model of a porous material, explain how porosity of a material affects the fact that the material absorbs sound.

Student's answer: "*If a material is very porous, its atoms are more separated and therefore, sound can rest within the spaces between atoms where there is air*" (S17C)

The previous answer evidences that the student thinks of porosity as a property of the material related to the distance between atoms. The fact that this student considers that "there is air between atoms" suggests a weak understanding of the particulate model of matter. Moreover, the student expresses that "sound can rest within the spaces between atoms." We interpret that the student conceives sound as an entity that can penetrate the material and remain there (Hrepic et al. 2010).

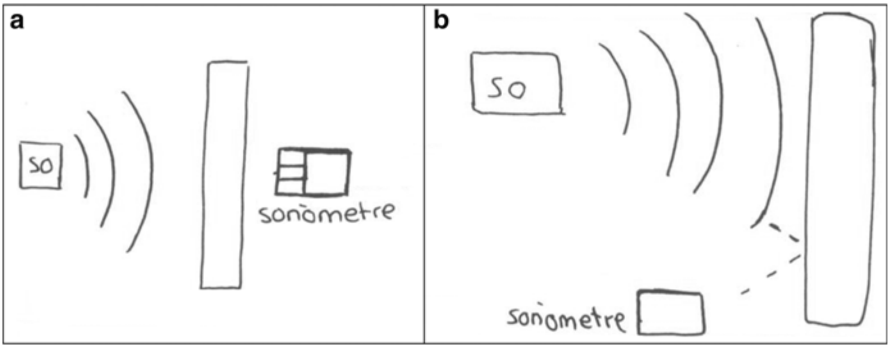
The lack of justifications of statements and predictions in terms of a certain conceptual model, as well as the use of certain terminology with an inaccurate meaning (e.g., reverberation as synonymous with echo, material as synonymous with object, elastic as synonymous with flexible), was also considered as students' conceptual difficulties.

7.1.1.4 Student's Needs or Difficulties Related to Experiments

Concerning the experimental tasks (DE), we could evidence some students' difficulties associated with certain practices, such as control of variables, design of experiments, analysis of empirical data, etc. As an example, the following drawing corresponds to the design of an experimental setup, drawn by a student in his booklet.

Question (V1): Draw a diagram of the experiment that you would carry out to test whether a material is:

(a) A good sound insulator
(b) A sound reflector



Student's drawing (S16A)

The previous drawing evidences that the design proposed by the student does not take into account that sound attenuation should be measured outside a closed space to avoid measuring the intensity level that corresponds to direct sound. The drawing does not indicate either that it is necessary to measure a reference value against which one can compare other measurements of sound intensity level in order to test if a certain material attenuates sound a lot or a little or reflects sound more or less than other materials.

7.1.2 Student's Needs or Difficulties Identified throughout the Implementations of Consecutive Versions of the Sequence

After having identified and categorized the types of students' needs and difficulties for each task of the sequence, we analyzed the prevalence of each type of difficulty during the implementation of the first, second and third versions of the sequence. Figure 2 presents a histogram showing the number and type of students' difficulties identified after the implementation of the first, second and third versions of the sequence. Thus, this graphical representation shows the evolution of students' difficulties as a result of the evaluation and refinement that were carried out from the first (V1) to the second versions (V2) of the sequence and from the second (V2) to the third versions (V3) of the sequence.

As shown in Fig. 2, the type of difficulty most commonly evidenced in the first version of the sequence is related to the use of concepts and conceptual models (DC). The histogram also shows that in the second version of the sequence, fewer difficulties were evidenced and the difficulties related to concepts were not the most frequent type of difficulty. Other sorts of difficulties (DO), such as students' lack of familiarity with the procedures of a certain kind of task (e.g., concept maps), were the most frequently evidenced during the implementation of the second version. The tendency towards a decrease in students' difficulties is also evident after the implementation of the third version of the sequence.

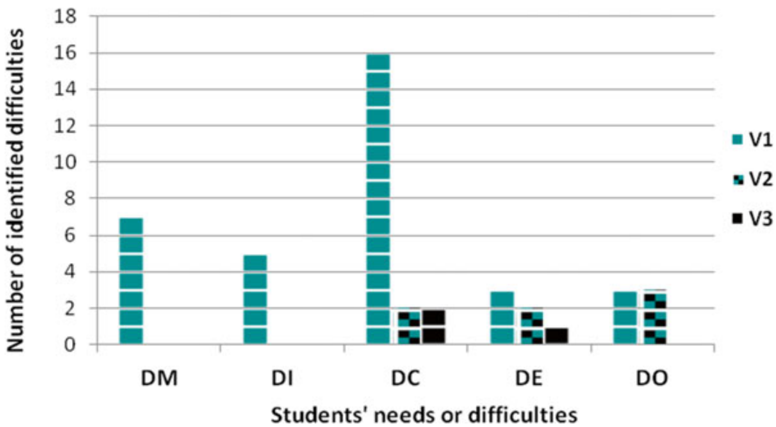


Fig. 2 Prevalence of students' needs or difficulties when implementing three consecutive versions of the sequence

Table 7 Types of changes introduced in the sequence when refining it

Code	Description
CQ	Reformulation of **questions/statements** of the sequence
CI	Re-elaboration of **diagrams, graphs and images** or introduction of additional **visual representations and their meaning**
CC	Introduction of additional **concepts** and **analogies or** adaptation of the **terminology**
CA	Addition or deletion of certain **activities**, re-elaboration of the **approach** of certain **activities** or modifications to the **structure of the designed sequence** (order of the activities)
CG	Addition of **guidelines/specifications** about how to do a task
CF	Modifications to **editing format**

7.2 On the Problematic Aspects of the Sequence and the Modifications Introduced

The analysis of the quality of the sequence also led us to interpret the problematic aspects of the sequence that might have resulted in certain teachers' and students' difficulties. Table 7 summarizes the types of changes that were introduced in the two first versions of the sequence (to obtain V2 and V3 of the sequence, respectively) when refining them according to the problematic aspects (in bold) of the sequence that were identified.

7.2.1 Types of Modifications Introduced in Consecutive Versions of the Sequence

The prevalence of each type of change introduced in the sequence after each cycle of refinement was also analyzed and represented graphically (Fig. 3).

As shown in Fig. 3, the most frequent types of change introduced in the first and second versions of the sequence are related to the addition, deletion or modification of certain activities re-elaborating their approach (CA). The histogram also shows that fewer modifications were introduced in the second version of the sequence in comparison with the first version.

7.2.2 Relationship between Students' Needs or Difficulties and Changes Introduced in the Sequence

Beyond the analysis of the number and types of changes introduced in the sequence when redesigning it, we focused on the possible relationships between these changes and students' needs or difficulties. The different changes were purposely introduced in the sequence in order to overcome the different types of students' difficulties previously identified. That is to say, each type of students' need or difficulty was addressed by a specific type of change in the sequence. The changes introduced in the sequence to deal with each type of students' difficulty are described below.

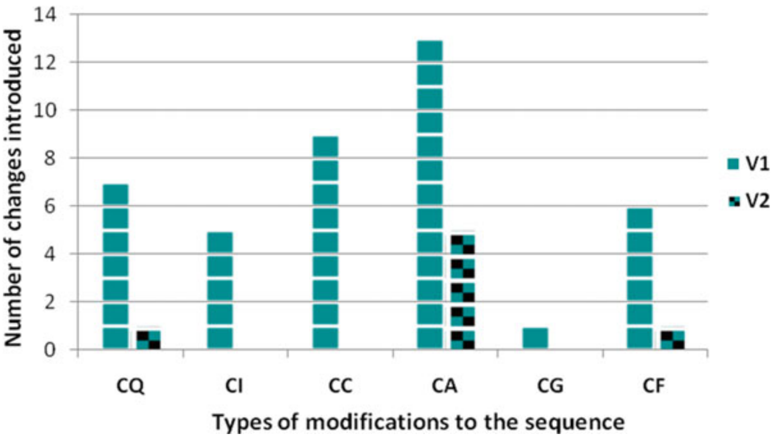


Fig. 3 Prevalence of types of modifications introduced in the sequence when refining consecutive versions of the sequence

7.2.2.1 Changes Introduced in the Sequence to Tackle Students' Needs or Difficulties Related to Metacognition

With the intention to overcome students' difficulties related to metacognitive aspects (DM), two types of changes were mainly introduced in the sequence: modifications to the questions or statements (CQ) and modifications to the activities (CA). The following example is intended to illustrate a change of wording introduced in the statement (CQ) of one of the activities of the sequence and the effect of these changes in students' answers:

Question (**V1**): From the measurements obtained in the previous tests, what conclusions can you reach?	→	**Question** (**V2**): From the graph you obtained, explain how the distance between the sound level meter and the buzzer affects the measurements of sound intensity level.
Student's answer: "*Our predictions [graphs] are quite similar to the real ones, but they would be more similar if there was not so much noise in the classroom*" (S01B)		**Student's answer**: "*The further [the sound level meter] is [from the buzzer], the less sound it can detect*" (S04A)

The answer of the students to the question, as formulated in the first version of the sequence, exemplifies that the modifications to the wording of a statement (CQ) in students' booklets result in students' identification of the aim of the question.

The next pair of statements corresponds to another task of the sequence that underwent changes in its approach (CA). That is to say, the activity was modified so that it keeps the same aim but the demand to students is adapted.

Question (**V1**): In the previous activities you developed an explanation about the influence of density, rigidity and porosity on the reflection or absorption of sound produced by materials. Now you can read how science explains the same relationships. [Comparing your explanation and the one elaborated by scientists] What should you improve in your model?	→	**Question** (**V2**): You have just read a scientific explanation that accounts for how density, rigidity and porosity of materials affect the fact that these materials behave as good sound absorbers. Based on the previous explanation, explain how sound reflectors attenuate sound and how their physical properties make them behave as good sound reflectors.

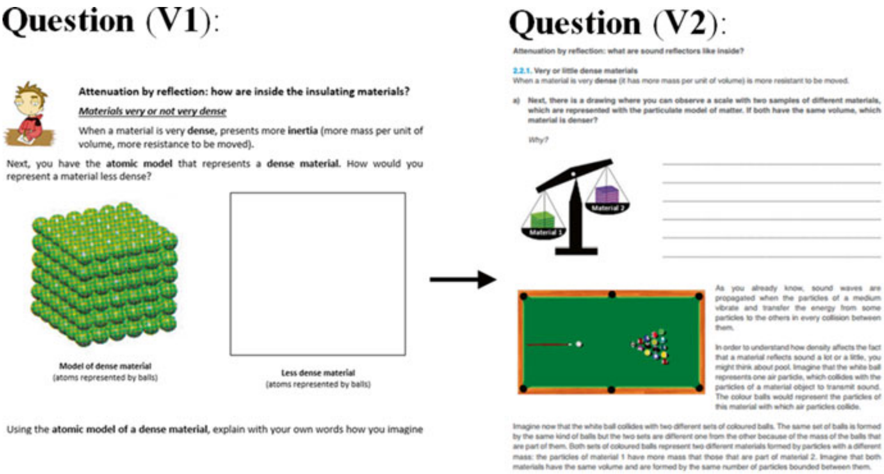
In this task, students were expected to reflect on how they explained sound attenuation in materials in terms of their properties and internal structure after having read and discussed a scientific explanation. About 70 % of the students did not answer the previous question in the first version of the sequence. We interpret that either these students might not be familiar with activities that involve comparison of explanatory models, reflection on and refinement of one's own models or they did not receive enough support to carry out the task, as formulated in V1. In any case, we decided to modify the approach (CA) of this activity in order to adjust the scaffolding provided to students in their necessary evolution of their preliminary models towards the intended conceptual models. The analysis of students' answers to the modified question (in V2 of the sequence) evidenced that about 90 % of the students accounted for the acoustic behavior of sound reflectors in terms of their internal structure and describing some mechanisms of sound attenuation.

7.2.2.2 Changes Introduced in the Sequence to Tackle Students' Needs or Difficulties Related to Images

The students' difficulties related to the interpretation of the meaning of images (DI) were mainly tackled re-elaborating diagrams, graphs and images or introducing additional visual representations and their meaning (CI). For instance, in the first version of the sequence, students were asked to interpret different images that represented phenomena (e.g., sound reflection and sound diffraction) by means of "sound rays" and wavefronts. The students attributed different meanings to both representations, considering in some cases that they are contradictory since students conceive that wavefronts represent sound propagating spherically in multiple directions but sound rays represent sound propagating in one direction. In the second version of the sequence, the meaning of these representations was explicitly introduced in an introductory chapter, explaining that sound rays in our didactical transposition indicate the direction of propagation of sound in which most of the energy is transmitted.

7.2.2.3 Changes Introduced in the Sequence to Tackle Students' Needs or Difficulties Related to Concepts or Conceptual Models

With the intention to overcome students' conceptual difficulties (DC) and to further scaffold the process of students' building of certain conceptual models, two main types of changes were introduced: introduction of the scientific meaning of certain concepts (CC), distinguishing it from the meaning attributed to them in everyday life, and modification to the approach of some activities (CA). We describe below the evolution of one of the activities from the first to the second version of the sequence, as an example of modification to the approach of an activity of the sequence to overcome certain identified conceptual difficulties of students.



The activity shown in the picture above asked students to represent the density of a material at the level of its microstructure in terms of the particulate model of matter. Moreover, they were asked to explain how density affects the acoustic behavior of materials in terms of their internal structure. In the first version of the sequence, the drawings made in this activity evidenced that about half of the students conceptualize density as being related to the distance between particles. Nevertheless, this conceptualization of density seems to be related to the attribution of corpuscular properties to sound (e.g., *"If a material is very dense, sound waves do not have space to enter or trespass because all the particles are very close to each other"* – S02A).

In order to support students' use of the particulate model of matter when conceptualizing density at the level of the internal structure of materials, some questions and an analogy (described in Table 2) were added in this activity. In the second version of the sequence, density is then conveyed as a property related to the molecular weight (and to inertia of particles). The questions introduced are intended to guide students' reasoning about the mechanisms of sound attenuation in terms of collisions between particles and resistance of particles to vibration, with the purpose of overcoming the conceptualization of sound attenuation as the process of "hindering the entrance of sound." In definition, the purpose of this activity did not change from one version to the next version, but the approach of the activity did.

7.2.2.4 Changes Introduced in the Sequence to Tackle Students' Needs or Difficulties Related to Experiments

Concerning the students' difficulties evidenced in experimental tasks (DE), various types of changes were introduced in the sequence to deal with those difficulties: adaptation of the approach of the tasks (CA), introduction of specific concepts (CC) and further guidance or specifications on the procedures of the task (CG). The activity described below is an example of an experimental task whose approach has been modified with the intention of supporting students in the design of an experiment intended to determine if a material behaves as a sound reflector or as a sound absorber.

Question (**V1**): How can we test empirically whether a material is a sound absorber or sound reflector?		**Question** (**V2**): How can we test empirically whether a material is a sound absorber or sound reflector?
(a) Prepare a list of materials and objects that you think you would need in order to do the experiment.	→	(a) How would you test whether the materials used to cover the ceiling and the walls of a disco are sound reflectors or absorbers?
(b) Draw a diagram or sketch of the experiment that you would carry out in order to test if a material is a good sound reflector.		(b) Draw a diagram of the experiment you would carry out in the classroom or in the laboratory in order to test if a material is a sound reflector or a sound absorber.

The previous activity was modified after having evidenced that students had difficulty devising experimental designs that can be prepared in a laboratory to solve real problems. In the first version of the sequence, students were posed the problem of a disco's owner who wanted to distinguish sound reflectors from sound absorbers to make an adequate choice of materials to treat the disco acoustically. After this contextualization of the activity, students were asked to design an experiment to distinguish sound absorbers from sound reflectors in the laboratory. In the implementation of the first version of the sequence, more than half the students (55 %, 36/65) proposed an inadequate experimental design to test whether a material behaves as a sound reflector or as a sound absorber. In the second version of the sequence, the approach of this task was modified so that students were first asked to devise a possible experimental design that real technicians could perform in the real context and then they were asked to adapt their design to the resources available in their school laboratories. This intermediate step turned out to be useful, since in the second version of the sequence, about 85 % of students described an appropriate and feasible experiment to test the acoustic behavior of a certain material in the laboratory.

7.2.2.5 Changes Introduced in the Sequence to Tackle Other Needs or Difficulties of Students

Finally, other difficulties (DO) identified in the implementation of the sequence, which are related to students' lack of familiarity with the procedures of a certain task or lack of written answers, have been tackled by changing the approach of the

Table 8 Critical reasons or "driving forces" to refine the sequence

Code	Description
DF1	Need for further readjustment/adaptation of the activities of the sequence to the intended "design principles" for improving validity
DF2	Need for tackling teachers' needs or difficulties in order to enhance the practicality of the designed sequence
DF3	Need for tackling students' needs or difficulties to enhance the efficacy of the designed sequence

activity (CA) to make it more familiar to students or adapting the format of the activities (CF) when editing the students' booklet.

7.3 On the "Driving Forces" or Critical Reasons for Change

To complement the description of the circumstances and agents involved in the process of iterative development of the TLS on APM, we consider it essential to report the critical reasons that have driven us to refine the sequence in the way we have done. These critical reasons or "driving forces" are summarized in Table 8.

Reflecting on the reasons that we argued for each of the changes introduced in the sequence, we establish some links between these reasons and the criteria to evaluate the quality of an innovation (van den Akker 1999).

7.3.1 Enhancing the Validity of the Designed Sequence by Readapting the Activities to the Design Principles (DF1)

According to Nieveen (2009), an innovation such as the TLS on APM is considered valid if it is based on state-of-the-art knowledge and if it is "logically" (or consistently) designed. Although it is clear that the design of the sequence was mainly based on theoretical assumptions and previous research results, its consistency needed to be appraised by comparing the intended design principles and the learning activities actually designed. This critical analysis was carried out resulting in the introduction of modifications to the sequence or in making explicit certain design principles that were used for the redesign. For instance, all the modifications to the organization of the activities[7] have been introduced after reflecting on the intended content structure of the sequence in order to group or reorganize the activities that deal with the same concept or phenomenon. Another type of modification influenced by this factor is the adaptation of the guidance provided to students in some activities to support their modeling processes or development of certain skills. Some of these changes were based on certain needs of students that had been evidenced, but they were also argued in terms of the intended design principles, which explic-

[7] The evolution of the structure of the sequence throughout the consecutive refinements of the sequence is represented in the Appendix.

itly highlight the need for providing gradual scaffolding and a variety of activities with different purposes throughout the sequence to support students in their learning process.

As a result of this critical analysis, we were able to readjust the designed TLS to the intended design principles and thus to enhance the validity of the designed sequence.

7.3.2 Enhancing the Practicality of the Designed Sequence by Tackling Teachers' Needs or Difficulties (DF2)

An innovation is said to be practical if it is realistically usable in the settings for which it has been designed and developed. Thus, only the users (teachers and students) of the designed sequence can evaluate if it is easy for them to use it in a way that is largely compatible with the developers' intentions. The fact that most of the teachers who implemented the sequence also participated in its design might undoubtedly have a positive effect on their perception of the practicality of the material. Nevertheless, the classroom observations and the discussions during the meetings of the LWG also evidenced some teachers' difficulties understanding the purpose of certain activities and thus providing guidelines to students for a certain task. Apart from discussing these difficulties among all the members of the LWG, the problematic activities which were identified were also adapted to facilitate teachers' understanding of these activities. This refinement contributed to enhancing the practicality of the designed sequence, as appraised by designer and non-designer teachers.

7.3.3 Enhancing the Efficacy of the Designed Sequence by Tackling Students' Needs or Difficulties (DF3)

An innovation is considered effective if it results in the desired outcomes. For this reason, the evaluation of the efficacy of the sequence was based on the analysis of the extent to which the experiences and outcomes of the intervention were consistent with the intended objectives. As reported before, an analysis of students' needs or difficulties was carried out and resulted in modifications to different aspects of the sequence intended to overcome those students' difficulties and to enhance students' learning outcomes in future implementations. Nevertheless, this chapter reports the analysis of students' outcomes during the implementation of the sequence but not at the end. The details of the analysis of students' learning outcomes at the end of the sequence are reported elsewhere (Hernández et al. 2014). This analysis evidenced a similar tendency towards higher achievement of students' learning outcomes throughout several refinements of the sequence. In short, the efficacy of the designed sequence, which was based on the results of the systematic analysis of students' outcomes during the implementation, was evaluated and improved throughout several cycles of refinement.

Finally, having argued the reasons for each change, we analyzed the weight of each reason over the total number of changes introduced throughout each iteration. Two main reasons or driving forces for the introduction of changes in the designed sequence were identified: (1) overcoming students' needs or difficulties (DF3), i.e., enhancing the efficacy of the sequence, and (2) realigning the activities to the intended design principles (DF1), i.e., enhancing the validity of the sequence. Fewer modifications of the activities were considered necessary to support teachers' needs (DF2), i.e., to enhance the practicality of the sequence.

8 Discussion and Conclusions

The analysis of the broad range of collected data, after two cycles of field testing, allowed for the evaluation of the quality of consecutive versions of the TLS on APM and identifying the main aspects and processes involved in the iterative refinement of the sequence.

First of all, the data collected during the implementation of the sequence were analyzed with the aim of identifying difficulties which had arisen during classroom implementation of consecutive versions of the sequence. *Two main types of students' difficulties were identified: those which evidence a lack of students' progress towards the achievement of certain intended learning targets* (e.g., difficulties related to concepts or conceptual models or difficulties related to experiments) *and those which indicate an unexpected or problematic realization of a certain task* and thus a possible factor that would hinder the achievement of certain intended learning targets (e.g., difficulties related to metacognition). As an example, the designed sequence contains certain activities that are intended to promote students' development of metacognitive skills, since they are considered relevant in themselves and, moreover, they contribute to promote students' achievement of intended learning targets. Although development of metacognition is not one of the learning targets addressed by the designed sequence, students' difficulties related to metacognition have also been taken into account to identify problematic aspects of the sequence and to refine the activities consequently. A remarkable result of the analysis of students' difficulties throughout the whole process of iterative refinement is related to the overcoming of most of these difficulties. *The decrease of students' difficulties derived from the refinement of the first version of the sequence is significantly higher than the decrease resulting from the refinement of the second version of the sequence.*

The identification of students' difficulties allowed the interpretation of several problematic aspects of the sequence in each cycle of development, which is the focus of the first research question of this study. The results of this research show that *the main aspects of the sequence that were interpreted as problematic* in the first iteration were *the approach and the organization of some activities. The concepts and analogies selected, the terminology used and the questions formulated in the sequence* were also interpreted as problematic aspects that had a strong weight in the refinement of the first version of the sequence. Comparing the first and the second cycles of field-testing of the sequence, we evidenced that fewer problematic aspects were identified in the second iteration, which indicates that the refinement carried out was rather effective. Furthermore, other patterns were noticed in the second iteration: (1) *not only were fewer activities considered problematic regarding their approach but also their organization was already considered appropriate* and (2) *the selection of concepts, analogies, terminology and images and the guidelines provided to students about how to perform certain activities were interpreted as adequate based on the evidence obtained from the previous analysis of students' difficulties.*

The second research question refers to the changes introduced in the sequence according to the problematic aspects that they address. The modifications were intended to deal with each type of difficulty identified after the implementation of each version of the sequence, such as students' difficulties related to experimental tasks or related to images. However, the identification of students' difficulties was not the only reason argued to introduce changes in the sequence. This result gives cause to discuss the third research question which deals with driving forces or critical reasons for changing different aspects of the sequence. Not only the analysis of data related to students but also the analysis of data related to teachers and the meta-analysis of the design principles of the sequence that brought several reasons to argue certain modifications to the designed sequence. These driving forces have been related to the criteria followed to evaluate the quality of an innovation, as described by Nieveen (2009), since after all, the reasons for change are intended to enhance the quality of the designed sequence.

In this sense, the improvement of the efficacy of the sequence along the process of iterative refinement has been described in terms of the evolution in number and types of students' difficulties and problematic aspects of the sequence. *The decrease in the number of identified difficulties for students evidences that the iterative development of the sequence has contributed to improve the efficacy of the sequence, from the point of view of students' performance.*

On the other hand, the enhancement of the validity of the sequence was carried out by consistently readapting the designed sequence to the design principles intended for the sequence. The weight that this "driving force" had on the process of refinement of the sequence highlights the *importance of making explicit and taking into account the theoretical assumptions and design principles of the designer group in order to enhance the quality of the sequence.* According to Ruthven et al. (2009, p. 329), "although iterative refinement of a design through analysis of its implementation is undoubtedly important, the cogency and efficiency with which such revision can be achieved is influenced by the quality of the original design and by the clarity and coherence of the intentions it expresses."

Finally, the quality of the designed sequence was also evaluated from the point of view of its practicality (or usability), in terms of the needs of the secondary school teachers who were part of the LWG. Unlike validity and efficacy, the evaluation of the practicality of the first version of the sequence gave rise to fewer changes, and moreover, no changes were introduced in the refinement of the second iteration in relation to teachers' needs. *At the end of the whole process of iterative refinement, teachers' perception of the practicality of the designed sequence and its innovative pedagogical approach was positive.*

An accurate interpretation of the improvement in students' performance must take into account that a successful innovation is a joint product of the designed intervention and the context (DBR Collective 2003). All the changes were agreed among the members of the LWG based on the evidence that had been obtained so that these modifications were decided with or positively received by the teachers who participated in the design and classroom implementation of the sequence. The decrease of teachers' needs or difficulties from the first implementation of the sequence to the second can be interpreted as a result of the internalization of goals on the part of teachers and their gradual familiarization with the innovative pedagogical approach and with the materials. Therefore, *the improvements in students' performance can be attributed not only to the iterative development of the designed sequence but also to teachers' increasing expertise and familiarization with the innovative sequence*.

In summary, the process of iterative development of the TLS on APM has been productive not only for supporting teachers when designing and implementing an innovative sequence and for enhancing the quality of the designed sequence but also for the knowledge on how to refine didactical innovations that this long process of research generates.

The "tracking" of students' realization in classroom tasks, the interpretation of students' and teachers' difficulties and needs, the elicitation of and alignment with the design principles and the identification of weak and problematic aspects of the sequence have turned out to be a useful and rich analysis to inform the process of refinement of the designed sequence towards improving its quality.

9 Recommendations

Although there is a great consensus about the importance of cyclical or iterative development of teaching and learning innovations in the field of research in science education, the recognition of the educational value of this process is not so extensive among the community of science educators and curriculum developers. As McDermott (2001, p. 1128) already stated, "instructors frequently judge the success of a new course or innovation by their impression of how much the students have learned or how satisfied they appear to be." This does not seem to be a valid indicator or criterion for evaluating the effectiveness of the instruction. At least, these perceptions are not reliable in guaranteeing the quality that is expected from an educational innovation.

The research study on the iterative development of a TLS on APM represents a contribution to the framework of design and development of TLSs, by reporting the process of refinement of the sequence and its implications on students' realization during the implementation of consecutive refined versions of the sequence.

In order to enhance the quality of a designed educational material, it is worth doing an in-depth analysis of students' performance and teachers' needs during its classroom implementation as well as an analysis of the alignment between intended design principles and the learning activities actually designed.

The research also provides a categorization of the types of problematic aspects identified during the implementation of the innovative sequence and the associated types of changes that can be introduced in the sequence in order to overcome some specific difficulties. This typology of changes can be applied to the development of other teaching/learning sequences on different topics.

Finally, another relevant result from this research consists of the refined research-based teaching/learning sequence on acoustic properties of materials (Pintó et al. 2009) that teachers can use in their science classes.

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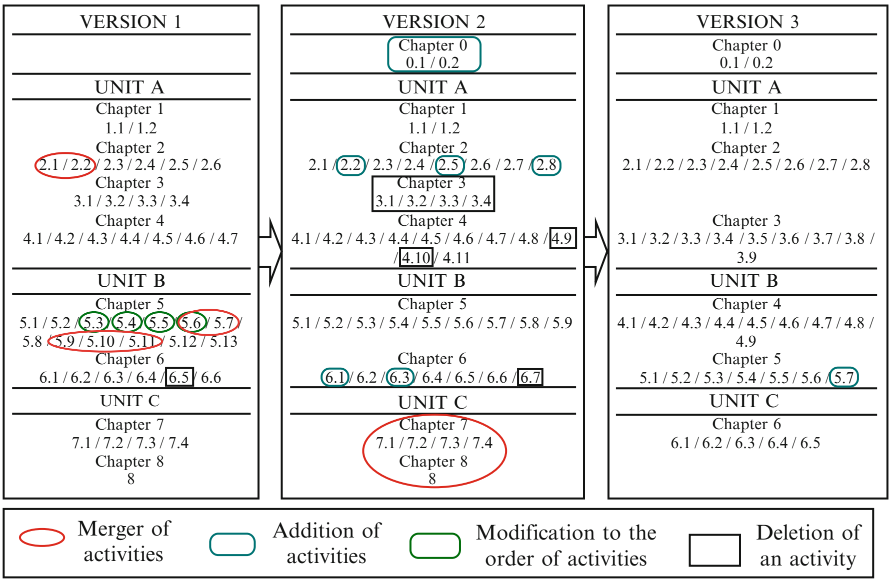
Appendix – Outline of the Evolution of the Structure of the TLS on APM after Consecutive Refinements



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The Evolutionary Refinement Process of a Teaching-Learning Sequence for Introducing Inquiry Aspects and Density as Materials' Property in Floating/Sinking Phenomena

Anastasios Zoupidis, Anna Spyrtou, Georgios Malandrakis, and Petros Kariotoglou

1 Introduction

Considering that TLSs have a discernible characteristic, which is their own gradual research-based evolutionary process (Lijnse 1995; Méheut and Psillos 2004), in this paper, we underline the development and the refinements from the first to the second implementation of an inquiry-oriented TLS focusing on the concept of *density* as a property of materials, in the frame of floating and sinking (F/S) phenomena. Pickering's (1995) theoretical framework and its subsequent adaptations (Kariotoglou et al. 2003; Patsadakis 2003) were used to analyze and describe the refinement process. Pickering's epistemological model includes three main factors affecting the refinement process: (1) the educational factor (e.g., curricula and educational tradition), (2) the material factor (e.g., experimental set-ups and laboratory classrooms) and (3) the scientific factor (e.g., teaching-learning theories such as constructivism and inquiry). From this analysis, we hope to reveal the content of these refinements, the main sources of data that indicated them and the role of each factor to the refinement process and finally to search if there are common characteristics of the refinements that are guided from the same factor.

Furthermore, a theoretical consideration about the dynamic that shapes the development of the TLS was developed. Specifically, there is a lengthy discussion in the science education community concerning the status that characterizes the evolutionary processes of TLSs (Lijnse 1995; Duit 1999; Méheut and Psillos 2004; Kariotoglou et al. 2003; Psillos et al. 2005; Fazio et al. 2008; Tiberghien et al. 2009). A number

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of researchers advocate that it is worth searching for evidence that indicates how and why a tested TLS is one of the best ways of teaching a topic and, as a result, to discuss the *didactical quality* of such a TLS (Lijnse and Klaassen 2004; Fazio et al. 2008). The *Didactical Structure* (Lijnse 1995; Lijnse and Klaassen 2004), the *Model of Educational Reconstruction* (Kattmann and Duit 1996; Duit 2007) and the *Didactical Rhobus* (Méheut and Psillos 2004) are three representative frameworks for elaborating and improving the design of a TLS. Despite the variations of these frameworks and the related interpretations, we could recognize their common focus on the research-based, evolutionary process of TLSs. In particular, these frameworks emphasize (1) the content to be taught (e.g., the elementary science concepts or appropriate teaching materials), (2) the research on learning and teaching (e.g., students' conceptions about physical phenomena and concepts or teaching-learning approaches) and (3) the development and evaluation of the TLSs implementations.

Furthermore, the analysis of designing a TLS extends towards the domain of research into scientific literacy, the crucial role of an educational system in which a TLS is embedded as well as towards the teachers who are disseminating the innovation of a TLS in school (Duit 2007; Besson et al. 2010). In particular, the curriculum, tradition of teaching methods, class organization, existing instructional materials and technical infrastructure are some of the educational system factors which affect the design of a TLS (Kariotoglou et al. 2003; Duit 2007). Essential factors for a TLS's introduction are regarded as (a) teachers' self-efficacy to implement a TLS (e.g., to feel that they enlarge their own knowledge about the topic to be taught) and (b) the close cooperation between teachers and researchers (Besson et al. 2010).

In line with the abovementioned consensus, the related research agenda tend to be oriented towards constructing theoretical backgrounds for designing TLSs (Kariotoglou et al. 2003; Psillos et al. 2004; Tiberghien et al. 2009). The intention of this research is to present theoretical contributions to the TLS design within the field of science education. We focus on an epistemological analysis which is based on Pickering's model (1995). This approach regards scientific practice as a "*changeable 'behavioural model' that unravels through the time*" (Kariotoglou et al. 2003). According to this statement, (1) TLSs are scientific products in the domain of science education and they have a changeable character; (2) a science educator researcher is the *science education* scientist who, through his/her practices, produces a TLS; (3) three factors (educational, material, scientific) constrain the various activities of a TLS development (resistance, accommodation, objective) and the connections between them. Science educators, in order to produce a TLS, accomplish their *objectives* and overcome the specific *resistances* implementing a process of *accommodation* (see Fig. 1).

The *educational* factor is associated with a particular school or classroom and refers to the everyday teaching-learning environments, the educational tradition of a school's district, its students' and teacher's characteristics (i.e., experience, inefficiency, difficulties etc.), the administration of a school and the parents of students. The *material* factor concerns the school's infrastructure, such as experimental setups, technological devices (e.g., PC), simple/everyday materials, laboratory classrooms (e.g., science or PC laboratories). The *scientific* factor is relevant to science education as a scientific activity and not to the traditional concept of science.

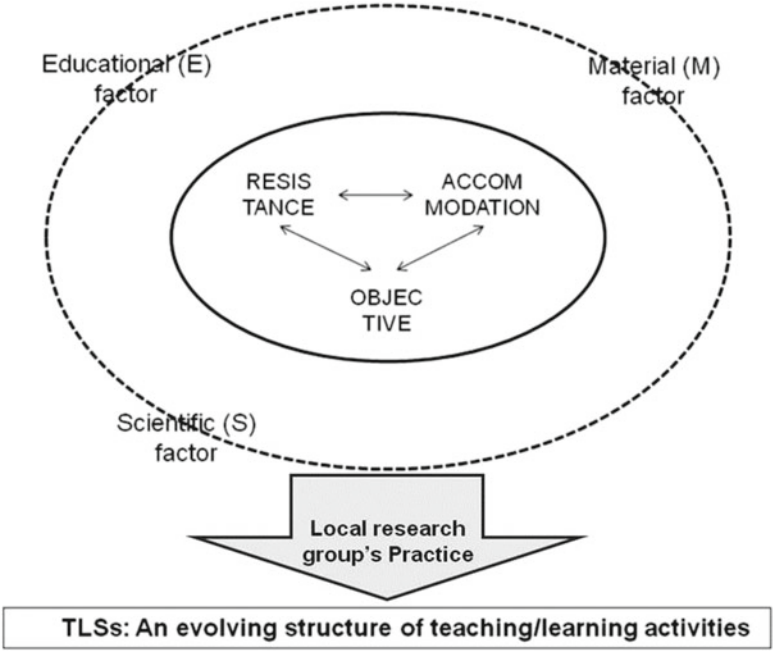


Fig. 1 The dynamic that shapes scientific practice in the development of a TLS (Kariotoglou et al. 2003)

More specifically, it concerns the literature trends and the dominant teaching-learning theories (e.g., constructivism, inquiry), particular aspects of these theories, such as the negotiation of students' conceptions and the introduction of modeling. The *objectives* pertain to the teaching objectives and expected learning outcomes, such as the learning of a scientific content or a scientific method. *Resistances* concern the difficulties that are confronted in the implementation of the *objectives*, including limited conceptual, procedural and epistemological learning. *Accommodations*, concerning the refinements that aim to overcome the resistances, could include modifications in the knowledge to be taught, the teaching methodology, instructional materials, etc.

From the abovementioned discussion, we believe that *Pickering's model* analysis, on the one hand, specifies the difference between the two areas, namely, science educational research and the area of educational systems, and, on the other hand, links them in a three-pole process, namely, the *objective-resistance-accommodation* process.

1.1 Density, A Property for Interpreting F/S Phenomena

Researchers who have studied students' conceptions of density (Smith et al. 1992; Hardy et al. 2006; Wiser and Smith 2008) consider that the difficulty in learning the notion of density is rooted in the fact that students appear to have already developed an alternative conceptual framework about matter and material kind. This framework is composed of perception-based physical quantities in which the raw scientific notions of weight, volume and density coexist.

In parallel, from the abovementioned literature, it is ascertained that F/S phenomena are common among students and, thus, suitable for the teaching of density, especially in primary and junior high school grades. Indeed, students seem to have a strong visualization of these phenomena (Joung 2009), which they explain and describe in terms of perception-based macroscopic natural properties, for example, weight, length and volume (Smith et al. 1992; Kawasaki et al. 2004; Havu 2005). More specifically, students formulate their estimation concerning floating of solid objects in water by taking into account (1) the dimensions of tanks in which floating takes place, (2) the weight of the bodies, (3) the depth of water, (4) the existence of hollows and (5) the shape of the floating object (Fassoulopoulos et al. 2003). Furthermore, other researchers (Perkins and Grotzer 2005) note that students, when interpreting F/S phenomena, use causal linear reasoning, i.e., referring only to an object's property instead of causal relational reasoning, i.e., comparing object and liquid densities in their interpretations. According to Perkins and Grotzer (2005), the shift from linear to relational reasoning in interpreting such phenomena is essential.

According to the abovementioned, the difficulty that students experience in understanding density as a property of material kind is mostly qualitative and conceptual and not quantitative. That is why Smith et al. (1992), followed by other researchers (Kawasaki et al. 2004), introduced the notion of density qualitatively, instead of using the relevant mathematical ratio (mass per unit of volume). In this approach, students were encouraged to develop their own conceptual models in order to interpret F/S phenomena and were prompted to work with a series of conceptual computer simulations.

In summary, there are two important shifts in the conceptual framework of matter and material kind that are considered to be necessary in understanding density as a property of materials: (a) moving from perception-based understanding of physical quantities (weight, volume, density) to a more objective and differentiated set of concepts, grounded in measurement and interrelated in a theory of matter, and (b) moving from causal linear to causal relational reasoning when interpreting F/S phenomena.

1.2 Inquiry Orientations, Control of Variables Strategy and Models Perspective

The realization of inquiry in science classrooms could be differentiated between "inquiry as means", that is, inquiry as an instructional approach or pedagogy, and "inquiry as ends", that is, inquiry as a set of instructional outcomes for students (Abd-El-Khalick et al. 2004). The first one, i.e., "inquiry as means", is recently referred to as Inquiry-Based Science Education (IBSE) in opposition to traditional deductive approaches (EU 2007) or under another perspective as full-inquiry or immersion units (Duschl and Grandy 2008). In both perspectives, learning should happen within a problem-based inquiry process, and inquiry is defined as debating with peers, planning investigations, searching for information, using and constructing models, forming coherent arguments, etc. "Inquiry as ends" is further differentiated into two sets of outcomes, being well documented, that students in grades 5–8 should develop: (1) abilities to do scientific inquiry and (2) understandings about scientific inquiry (Bybee 2006).

Fundamental understandings of scientific "inquiry as ends" in education, among others, are associated with the adoption of control of variables strategy (CVS) elements and the nature and role of models. More specifically, the CVS method (Boudreaux et al. 2008) is used to characterize whether or not a variable influences the behavior of a system. Procedurally, CVS is a method for (a) designing experiments and (b) implementing experiments (Kariotoglou 2002; Toth et al. 2000). Conceptually, CVS is based on the ability to evaluate an experiment as a *good* or *bad* one (well-controlled or not controlled experiment) as well as the ability to draw conclusions based on the evidence of *good* experiments (Toth et al. 2000; Boudreaux et al. 2008). According to literature, students basically experience the following difficulties with scientific reasoning related to CVS: (a) failure to distinguish between expectations and evidence, (b) reluctance to make inferences from data, (c) failure to control variables, (d) failure to realize that a variable must be changed to test for its influence, (e) failure to design experiments for the test of two focal variables (NRC 2000; Boudreaux et al. 2008).

Models, namely, representations of an object, a concept, a process or a phenomenon (Halloun 2004), are also considered as facilitators of conceptual understanding and achievement in school settings, because of their importance in the development of metaconceptual awareness, metacognitive skills and intentional learning (Vosniadou 2010). Learning, using, revising and constructing models are the most important acts of modeling that should be adopted in science classrooms (Justi and Gilbert 2002). Nevertheless, there is some evidence that difficulties in the instruction could arise from students' alternative ideas of models. For example, students that consider models as a precise representation (i.e., a replica) are constrained to understand the concept of scientific model (Treagust et al. 2002) as well as of abstract scientific concepts like density (Wiser and Smith 2008). Besides, it is known that students in primary school mainly hold a recreational view concerning the models (Gilbert 1991; Treagust et al. 2002). That is, students' interpretation of the term scientific model depends on their experiences and personal understandings. Consequently, researchers (Treagust, et al. 2002; Vosniadou 2010) argue that students, apart from acting with models, should develop understandings about their nature and role as well, i.e., that models, at all levels, are analog representations of reality and not their copies, that they serve as a tool and not as exemplar and, finally, that their main role is to explain and predict (Treagust et al. 2002). Furthermore, Petrosino (2003) argues that it is more fruitful to introduce students to modeling practices through models that preserve resemblance, because these models more readily sustain mappings between the model and the world. So, as students learn over a number of cases that resemblance is less fundamental than function, they become increasingly prepared to work with models that do not preserve similarity between the model and the modeled world.

To summarize, it should be noted that both "inquiry as means" and "inquiry as ends" should be important elements of inquiry in contemporary science classrooms. On the one hand, IBSE should be seen as a spectrum of approaches from open inquiry, in which students take the lead in acting and inquiring, to more structured inquiry, in which teachers determine the questions and specific procedures of the investigation (Crawford 2007). On the other hand, inquiry abilities and understandings to be acquired constitute another spectrum, elements of which are both CVS and models.

2 The Context of the Study

According to the Greek curriculum, it is proposed that the concept of density be introduced in the fifth grade (10–11 years old) of primary school, as a property of materials. This introduction comprises a limited number of examples including the sinking of a real ship. F/S phenomena are studied neither in the fifth nor in the sixth grade. More specifically, it is proposed that the negotiation of the phenomena/concepts be implemented through a guided discovery approach. In each lesson, students should be asked to implement the following learning approach: brainstorming, hypothesis, experiment, observation, verification or rejection of the hypothesis, drawing a conclusion and generalization. One of the aims referred to in the Greek curriculum is the understanding of this specific scientific method by students. However, the majority of teachers implement traditional deductive teaching-learning practices, followed by experiment demonstrations, while group experimental work is very rare. The innovation, whenever it exists, is confined to some environmental education programs, which are sporadic, and, although encouraged by the official curriculum, no means and motives are given for them to be undertaken. The aftermath of this educational tradition is the limited students' and teachers' experience concerning inquiry and modeling teaching-learning environments.

3 Design of the TLS

In this section, we will discuss the major TLS's design principles. An important one was the participative character of its development. A group of researchers and teachers was in charge of designing and developing the TLS. The design principles presented in the next paragraphs were mainly set by the researchers who designed and developed the TLS teaching scenarios. The teachers discussed with the researchers the nature of the TLS activities, their own understanding of the activities, the possible student difficulties that they could figure out, possible changes that they would propose and/or ways of implementing these activities. This process took place over a two-month period before and during the first implementation.

We consider this TLS to be a part of a larger sequence of TLSs, designed to bring about a restructuring of student frameworks for thinking about matter and material kind. This TLS focuses on the concept of *density*: (a) in a qualitative way, i.e., as a property of materials, instead of the quantitative approach of mathematical ratio, and (b) in the frame of F/S phenomena of several objects (both/either homogeneous and/or composite) in everyday life, e.g., that of a ship. Studying F/S phenomena revealed that the negotiation with the variables affecting these phenomena becomes an important teaching issue. Having in mind that students should be helped to understand the variables that influence the F/S phenomena, CVS is assumed to be an appropriate instructional tool to achieve it. Because of the limited students' inquiry experiences, it was decided that the CVS method should firstly be demonstrated by the teacher and afterwards applied by the students in a two-step and strictly guided way.

In addition, a technological-problem scenario was developed, which is based on the intention to salvage the *Sea Diamond* shipwreck. This shipwreck received wide media coverage in April 2007 in Greece. We assume that this scenario is an authentic context in which technological and scientific issues coexist. Furthermore, this real technological problem is the vehicle to design trans-disciplinary activities trying to create the path from technological to scientific inquiries and vice versa, aiming at the interweaving of scientific and technological knowledge. We assumed that the use of authentic contexts in which technological and scientific issues coexist would enhance elementary students' interest in science learning. We based this belief on literature, arguing that the integration of technology with science teaching-learning (1) promotes active learning, (2) helps to improve academic performance and students' attitudes towards science and (3) reinforces positive interaction between teachers and students, providing the latter with opportunities to engage in authentic inquiry processes that scientists actually carry out (Waight and Abd-El-Khalick 2007; Benett et al. 2007). The hope is that the technological contexts will motivate students and make them feel more positive about science by helping them see that *science is everywhere*.

Adopting the IBSE approach, the aim was to give students the opportunity to (a) work in groups realizing real and simulated F/S experiments in order to interpret them or to find solutions to technological problems such as the salvaging of a ship, (b) use and understand CVS reasoning, (c) search for information about the properties of new materials, (d) learn and use a visual model of density in order to develop causal relational reasoning in interpreting F/S phenomena, (e) communicate their understandings in their group and in class. In order to enhance the abovementioned approach, we designed and developed, from scratch, a software (Spyrtou et al. 2008) having at least the following features: (a) playful character with profound interactive elements; (b) semi-open approach, which allows experimenting in a controlled environment; and (c) separation in *rooms*, which will follow the development of teaching.

CVS and *nature and role of models* elements were the inquiry abilities and understandings that students were expected to acquire (for details, see Sect. 4). Our primary assumption was that by involving students in a discussion about these two main epistemological aspects of scientific inquiry, they could really enhance their own understanding about them.

4 Development of the TLS

The TLS consists of five units, each of which lasts for 80 min. Hereafter, we will describe the units of the first implementation (Table 1). In the first unit, the students are introduced to the technological problem of the salvage of the *Sea Diamond*'s shipwreck through a video which includes a description of the accident and a discussion about its environmental consequences. Furthermore, the students are familiarized with F/S phenomena through several activities such as real experiments working in a predict-observe-explore (POE) approach. Following on, students discuss and try to predict, under the teacher's guidance, the variables that possibly affect F/S. In the end, the teacher enounces the scientific method used in order to test if a variable affects a phenomenon, that is, CVS method. The teacher, following the steps of the method, tests if the shape of an object could affect the F/S of the object.

In the second unit, the students, working in groups, follow the POE approach in a simulated environment, testing several variables according to structured worksheets. These are guiding students in an inquiry procedure, using CVS method by following three steps: (a) to keep constant all the other variables except for tested variable, (b) to experiment at least twice in order to compare the results and (c) to

Table 1 The content in each unit of the TLS, in the first implementation

Unit	Content
First	The shape of an object does not affect its F/S in water
	The crucial steps of the CVS method
Second	The variables that affect F/S of an object are both the kind of material of the object and the kind of liquid
	The weight of an object or the width of a tank does not affect its F/S in a tank
	The crucial steps of the CVS method
Third	Object-water *dots-per-cube criterion* for F/S
Fourth	Density can be represented by *dot crowdedness* model for each homogeneous material
	Density of a composite object lies between the densities of the two materials
	Object-liquid *density's criterion* for F/S
	Study of natural and artificial materials' properties
	Basic features of the nature and role of models
Fifth	*Density's criterion* used as a predicting tool in a series of technological F/S situations

Fig. 2 The visual *dot crowdedness* model of several materials

draw a conclusion according to the observations. In these inquiries, the focal variable and the method that students should apply are given, in the sense that their observations are guided. In addition, they communicate their groups' conclusions in the class.

In the third unit, the students are introduced to a precursor visual model of density as a property of materials, the *dot crowdedness* model (Smith et al. 1992, Fig. 2). Firstly, the students are called to propose their ideas about how to represent the *heavier-lighter* relation between three cubes of the same volume but of different material. After this discussion, the teacher proposes the *dot crowdedness* model as another possible representation for the *heavier-lighter* relation. As a next step, they are called to predict the F/S of several objects in several liquids. Our aim is to lead students to realize the necessity for a criterion in order to confront the difficulty of predicting the result of the phenomenon. Using simulated environments, students are expected to acquire a causal relational reasoning (Perkins and Grotzer 2005) in order to explain and predict F/S phenomena for homogenous objects. More specifically, students are expected to acquire and use the object-water *dots-per-cube criterion*, that is, *if dots-per-cube of an object are fewer than the same-size dots-per-cube of water, then the object will float in the water* and *if dots-per-cube of an object are more than the same-size dots-per-cube of water, then the object will sink in the water*.

In the fourth unit, instead of the concept *dots-per-cube* of a material, the concept *density* of a material is also introduced. As a consequence, students conclude the object-water *density's criterion*: *if an object's density is smaller than water's density, then the object will float in the water* and *if an object's density is greater than water's density, then the object will sink in the water*. They are also prompted to work in groups in order to generalize the object-liquid *density's criterion* for F/S (see Sect. 7.4.2). Furthermore, students are negotiating situations of F/S of two-material composite objects, for instance, a bottle filled with air or a bottle filled with water. Our aim is for the students to understand that the density of a composite object, which consists of two materials, lies between the densities of the two materials. Hence, they are supposed to extend the use of the *density's criterion* to composite objects as well, and so come closer to the technological world, in order to confront authentic technological problems in the next unit. In addition, students collect information about several natural and artificial materials and discuss their density as well as their use and the possible environmental problems they create. Finally, they are introduced to the concept of *model* and its features through a discussion about the models of ships and the models of density that they already used during the previous units. Furthermore, they negotiate about the features of two heliocentric models, a picture and a concrete model, that a teacher has brought into the class. During this discussion, the focus is on basic features of the nature of models, such as (a) a model is a representation of a target; (b) a model is not a copy of a target; (c) a target could be represented by more than one model; (d) the role or purpose of a model is to describe, explain or predict a phenomenon; and (e) a model is not a recreational or instructional medium (Treagust et al. 2002; Gilbert 1991).

In the fifth unit, students have the opportunity to work in groups in a simulated environment and investigate the F/S of the *Sea Diamond* cruise ship, in order to argue about its salvage. Students are also confronting the technological problem of salvaging, in a real setting, a model of a clay statue and an iron ship model which are both immersed in tanks filled with water. Students are negotiating these problems in a technological frame, that is, they are prompted to take into account features such as the possible risks and costs of the enterprise.

5 Implementations of the TLS

The first implementation was conducted during November and December 2007 in a primary school of Florina, Greece, with 12 fifth grade students (10–11 years old). The primary teacher of the first implementation holds a master's degree in ICT in education and has 9 years of teaching experience, the last 2 of which were exclusively dedicated to teaching science to fifth and sixth grade students. After the refinement process, a second implementation was conducted, during March and April 2008, by another teacher in another Florina primary school, with 41 fifth grade students (two classes). This teacher had 23 years of teaching experience including 8 years as a science mentor to pre-service students in the Department of Primary School Education of Florina.

The first implementation took place during normal daily courses. We reduced the number of students for technical reasons, because it was difficult to videotape the implementation due to the small size of the class. The second implementation took place during normal daily courses, but in this case, the classroom was large enough so the whole class could be videotaped.

Furthermore, because of its innovative nature, permission to videotape the intervention was requested from all educational authorities (consultants, headmasters, teachers, parents and students).

6 Research Methodology

The main concern of this paper is related to the disclosure and the classification of the TLS refinements from the first to the second implementation. The participants who were involved in this process were (a) the students, (b) the teachers, (c) the four science education researchers of the local group (researchers) and (d) the expert panel of the project (experts).

So, the research questions of this endeavor are the following:

1. Which were the refinements that took place between the first and second implementation of the TLS and to which content do they relate?
2. Which were the main sources of data that contributed to the refinement procedure?
3. Which of the three factors of Pickering's model guided the local research group to proceed to these refinements?
4. Are there common characteristics among the refinements that are guided from the same Pickering factor?

In order to answer the aforementioned research questions, we elaborated the following first implementation's sources of data: (a) researchers' classroom notes (researchers' notes), (b) experts' and teachers' suggestions, (c) students' worksheets, pre- and post-questionnaires (given to the students one week before and one week after the intervention of the TLS, respectively), video recordings.

TLS's refinement process began just after the completion of the first implementation. This process took place during several meetings of the local research group. Each of the participants, though, contributed in a different way and to varying degrees. The researchers, for example, had the main responsibility for the design and redesign of the teaching scenarios taking into account teachers' suggestions. In addition, they followed the implementation of each unit taking notes about the difficulties that either students or teachers had during the lessons. The experts contributed as distant consultants based on the teaching scenarios and the descriptions of the difficulties given by the researchers. The teacher's role, during both the development and the refinement of the teaching scenarios, was mainly advisory, and their suggestions were mainly focused on the difficulties they or the students confronted during the first implementation, making suggestions to overcome them. In addition, in order to establish the significance of researchers' notes or teachers' suggestions, these were crosschecked and associated with specific parts of the students' worksheets, pre- and post-questionnaires or/and teaching video recordings. Therefore, we consider researchers' notes as well as experts' and teachers' suggestions as the primary data sources in the refinement process, while students' worksheets, pre- and post-questionnaires and teaching videos were taken as secondary data sources. The analysis of all these data was performed by the researchers. Nevertheless, each refinement came of through a consensus among all the members of the local research group.

After the second implementation of the TLS, the local research group identified these refinements comparing the two TLSs (first and second implementations). We analyzed each of the refinements following *Pickering's model* (see the Introduction). In our case, there is a TLS innovation which has several *objectives*. The analysis of the abovementioned data provided the *resistances* that influenced and directed the researchers towards specific *accommodations*. Having in mind that Pickering's model interprets scientific production in general, we consider that in our case, it can be used to interpret the evolutionary design and development of a TLS and, more specifically, the process of its refinement, in the sense of a cyclical process of recon-

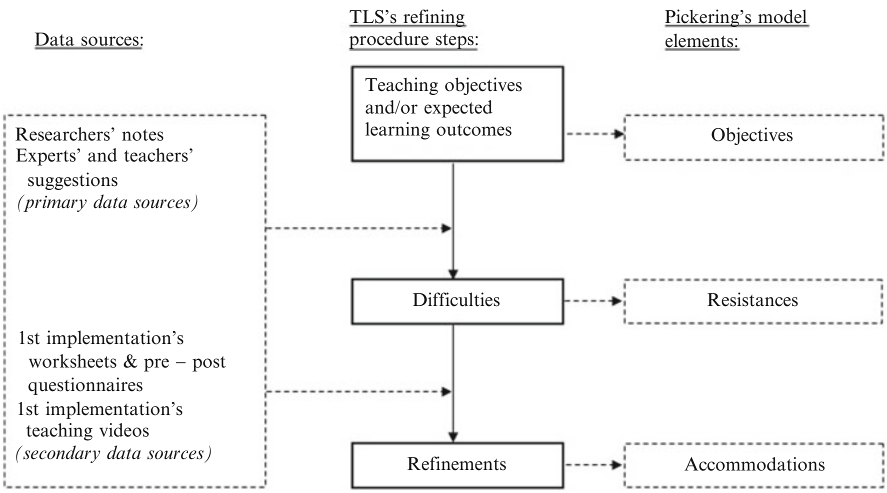


Fig. 3 TLS's refining process flow chart from the first to the second implementation

sideration. We consider that our refinements correspond to Pickering's *accommodations*. In addition, we consider that the difficulties each participant of this project confronted correspond to Pickering's *resistances*. Finally, teaching objectives and expected learning outcomes correspond to Pickering's *objectives*. The abovementioned analysis following Pickering's model was performed by two members of the local research group independently, reaching 80 % consensus initially. However, all disagreements were solved after discussion between the researchers.

The TLS's refining process in relation to the elements of Pickering's model is illustrated in Fig. 3.

The presentation of the results, i.e., the refinements, follows the respective content of the TLS, that is, (a) reasoning concerning F/S phenomena and (b) density as a property of materials, which are considered as declarative knowledge, (c) CVS method and (d) the nature and role of models as well as model use, which are considered as both procedural and epistemological knowledge.

7 Results

In total, fifteen refinements of the TLS took place following the *objective, resistance, accommodation* structure (see Tables 3, 5 and 6). In addition, each refinement was associated (a) to the Pickering factor(s) that mainly guided this accommodation and (b) to the data sources, both primary and secondary, that influenced them. Due to lack of space, only representative refinements of each category will be analytically described. Throughout this evolutionary process, one, two or even all three factors (educational, scientific or material) could be involved, having though different degrees of influence. We consider that the main factor that guides a refinement is (a) the educational factor if the origins of the refinement are teachers' experience or/and students' difficulties, (b) the scientific factor if the roots or the origins of the refinement are literature trends or/and dominant teaching-learning theories and (c) the material factor if the root or the origin of the refinement is, for example, school infrastructure.

7.1 Reasoning Concerning F/S Phenomena

Two refinements have been made concerning F/S: (a) a connection between real and simulated experiment interpretations and (b) a reduction in the time devoted to the familiarization phase. The first refinement is described analytically in the following section, while the second is presented in Table 3.

7.1.1 F/S, Connection between Real and Simulated Experiments Interpretations

Objective One of the intended goals of the TLS is the use of the concept of density in the explanations given by students about the F/S phenomena in a relational way, i.e., by comparing the density of the object with the density of the liquid (Perkins and Grotzer 2005). A moderate expected learning outcome could be the reference to the material of the object (Smith et al. 1992).

Resistance The resistance was initially triggered by the experts' suggestion of a better balance between the real and the simulated experiments concerning the negotiation of the F/S phenomena of the TLS because of the students' young age. It was considered difficult for the students to grasp the relation and analogy between simulations and real situations. This difficulty was established by the results produced from pre- and post-questionnaires of the first implementation, concerning the explanations given by students when asked about F/S phenomena. There are questionnaire tasks which negotiate everyday environment situations (e.g., task A, "A ball made of plasticine is sunk in a tank of water. Could you make it float? How?"), as well as simulated situations (e.g., task B, giving them the opportunity to use the *dot crowdedness* model in order to decide if an object will float or sink). Based on the results of these two indicative tasks and especially the post ones (Table 2), we argue that the students give answers closer to the expected learning outcome when they confront simulated rather than real situations.

The comparison of the abovementioned results permits us to assume that the students find it difficult to apply to real phenomena what they have learned in a simulated environment. We thought that one way to overcome this difficulty could have been to increase the comparatively smaller amount of real, in relation to the simulated, experiments being processed.

Table 2 Categories of student's explanations of F/S phenomena

	Real experiments – Task A		Simulated experiments – Task B	
	Pre	Post	Pre	Post
Compare the density of the object to the density of the liquid or refer to the material of the object	1[a]	3	–	10
Refer to the weight of the object or teleological answers	11	9	–	2

[a]Number of students expressing the particular explanation

Accommodation Due to the abovementioned reasons, we proceeded to the following changes: (a) the number of the real experiments was increased from eight to ten, and the simulated ones were reduced from 16 to 15; (b) three of the activities that, in the first implementation, were performed by the teacher, in the second implementation, were performed by groups of students; and (c) students were prompted to associate their explanations given in simulated experiments with those given in the real ones. The latter aimed to increase students' active participation in real experiments, in expectation of a consequent enhancement of their explanations of F/S phenomena in real situations. Although this accommodation was initiated by the experts, it was considered that the educational factor has mainly guided this refinement, as the main issue was students' difficulties and how to overcome them. On the other hand, in a secondary manner, the refinement was considered to also have been guided by the scientific factor, because the teaching method was changed from demonstration to group work, following science education literature trends.

7.2 *Density*

7.2.1 Density, Emphasis given to the Distinction between Homogeneous and Composite Objects

Objective Another intended goal of the TLS is for students to use the visual model of density in order to explain and predict F/S phenomena of both homogeneous and composite objects. More specifically, the students initially are called to negotiate the F/S of homogeneous objects, like cubes or spheres made of one material, for example, wood or plastic, using the *dots crowdedness* model and the object-liquid densities comparison criterion. Next, they are called to apply the same criterion to composite objects like a bottle made of glass or an iron-made model of a ship filled with air or water.

Resistance It appeared, according to the researcher's notes, that in order to understand the concept of density of an object, the students should make clear the distinction between the concepts of homogeneous and composite objects (because of their age, we only used two composite parts). During the first implementation, this discussion took place at the end of the TLS and specifically at the beginning of the fifth unit (Table 1). The resistance occurred because most of the students could use the *dot crowdedness* model in a causal relational reasoning in order to predict and explain the F/S of homogeneous objects, but they found it difficult to do the same for composite objects, e.g., an iron model ship filled with air or water, even though the teachers prompted them to do so. The following excerpt from classroom video recordings is indicative:

Student A: (tries to use density in order to explain the iron ship floating). This ship is made of… it has air inside and the air has less density than the iron and the water… the ship has air inside and the air holds the iron up.
Student B: because air floats on water and that's why the ship floats.
Teacher: Yes, the ship is made of iron and has air inside.
Student C: It is like a life-jacket.
Student D: Buoyancy is created. Because this has air inside, like student C correctly said, it is like a life-jacket, and because it has air inside it floats…

So, the students' explanations turned into causal linear reasoning instead of the causal relational, with the main variable influencing F/S being the existence of air in the object.

Table 3 Pickering's model concerning F/S and density refinements

Objective	Resistance	Accommodation	Factor	Data sources
7.1.1. Explaining and predicting F/S phenomena for homogeneous objects	Less efficiency in interpreting real than simulated experiments	Connection between real and simulated experiments interpretations	E, S[a]	Experts' suggestions
		From demonstration to group experiments		Pre – and post-questionnaires (analyzed by the researchers)
7.1.2. Familiarization with F/S phenomena	Much time was devoted to this objective	Reduction of the time devoted to the students' familiarization activities, in favor of the introduction of aspects of the nature and role of models	E	Teachers suggestions
				Students' worksheets
7.2.1. Explaining and predicting F/S phenomena for composite objects using the dot crowdedness model	Limited knowledge in using density of composite materials in F/S	Emphasis given to the distinction between homogeneous and composite objects	E	Researchers' notes
		Immediate approach to the visual dot crowdedness model during the relevant discussions		Videotaped lessons

[a]*E* Educational, *M* Material, *S* Scientific

Accommodation In the second implementation, the discussions that aimed at the use of the visual model of density for the explanation of the F/S phenomena of homogeneous and composite objects were presented as follows: (a) the concept of homogeneous objects was introduced and discussed during the first unit, and the concept of the composite objects, during the fourth unit and (b) the students were prompted to use the *dot crowdedness* model in their explanations of composite objects' F/S phenomena during the fourth and fifth units.

Consequently, it was considered that the educational factor has mainly guided this refinement since it occurred due to student difficulties.

7.3 Inquiry Skills – Control of Variables Strategy (CVS)

Six refinements have been recognized concerning inquiry skills, with five of them being relevant to the CVS: (a) from demo and guided to more open inquiry approach, (b) emphasis on drawing a conclusion procedure, (c) changes in the order of the focal variables, (d) two tests instead of three and (e) changes in teaching materials used to reveal variables of F/S phenomena, while the sixth refinement concerns searching for information in texts: (f) changes in visual material. The first three refinements are discussed in detail in the following sections, while the rest are presented in Table 5.

7.3.1 CVS, From Demo and Guided, to More Open Inquiry Approach

Objective This refinement refers to the degree of guidance, hence the teaching method, according to which the students tested the variables that probably affect the F/S of an object in a liquid (see Sect. 4, development of the TLS, units 1 and 2). We thought that students needed this significant guidance to apply the method because they are not familiar with similar inquiries. We also assumed that the students would acquire the method, just using it in F/S phenomena, in the way described in Sect. 4.

Resistance The experts made the provocative suggestion of turning to an open instead of guided inquiry approach. In parallel, it was clear that the students confronted difficulties in acquiring the method (see Sect. 7.3.2). However, guided by the inquiry paradigm and following expert suggestion, we insisted on the acquisition of the reasoning of the CVS method adopting a more open inquiry approach.

Accommodation As a result, in the second implementation, the method aimed at the gradual increase of students' active participation, i.e., the gradual increase of the degree of *openness* of the inquiry procedure. At first, the teacher demonstrated the CVS method, and particularly, she tested the variable *weight* of the object. Next, the students tested the variable *width* of the tank, in groups, by using structured worksheets, in which the appropriate method is clearly given. Then they tested the variable *kind* of the liquid, for which they were asked to design the experiment they were to carry out. Finally, in the last level of inquiry *openness*, the students were asked to design and implement an experiment or experiments in order to test two variables: *kind* of the object's material and *shape* of the object, without any other guidance.

The determining factor that led the research group to a more open inquiry approach was expert suggestions. Despite the students' difficulties in acquiring CVS method, which should lead to a more guided approach, this decision was obviously affected by inquiry literature trends. Consequently, it was assumed that it was mainly the scientific factor that guided this refinement.

7.3.2 CVS, Emphasis on the Drawing a Conclusion Procedure

Objective A main element of the CVS is drawing a conclusion procedure. In the first implementation, it was expected that the students would acquire this procedure just by participating in guided experimental activities.

Resistance Nevertheless, there was evidence which emerged from different data collection tools that highlighted the fact that the students experienced difficulty in understanding the rationale of the method. The first clue comes from the researchers' notes during the third unit: "at the beginning of the lesson the teacher poses a review question about which variables eventually affect the F/S of an object. The students at first mention all the variables that they had tested in the first two lessons and answer that all these variables affect the F/S phenomena." The observation is enforced by videotaped transcriptions analysis.

Moreover, results from the pre- and post-questionnaires (Table 4) showed that the students had great difficulty in understanding the drawing a conclusion procedure and especially the importance of evidence in this procedure.

Accommodation As a result, we decided to teach the drawing a conclusion procedure in an explicit way, following the suggestions of the relevant literature, which indicates that the importance of the extra teaching on this part of scientific reasoning is still an open field for further investigation (Boudreaux et al. 2008; Toth et al. 2000). Hence, a representation (Fig. 4) of the drawing a conclusion procedure, like the rationale *If… then…, while if… then….*, was explicitly presented to the students.

Table 4 Students' understanding of the drawing a conclusion procedure

	Pre	Post
Correct description of CVS	0	0
Partially correct description of CVS	1	2
Expression of the inference instead of the CVS	7	9
Incoherence of description	4	1

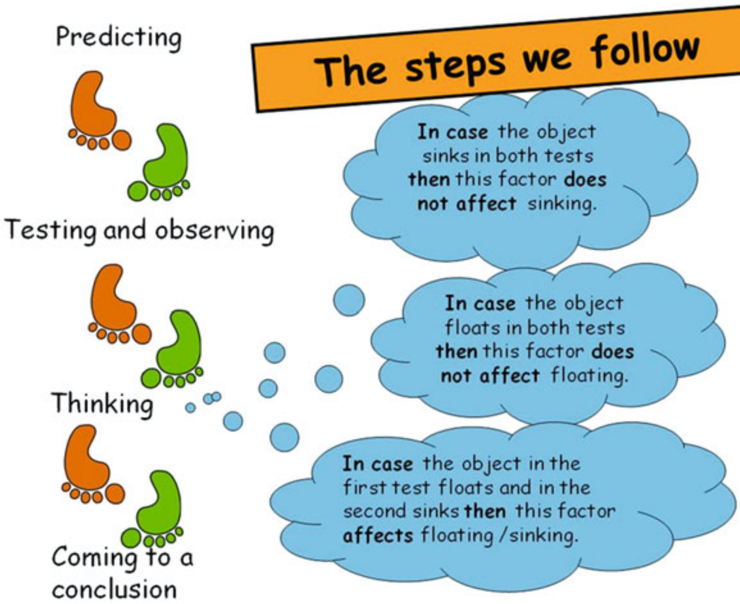


Fig. 4 A representation of the drawing a conclusion procedure, emphasizing "thinking" step

Moreover, the teacher was guided by the research group to give more time to the students to participate in the relevant discussions and thus to present and argue their opinions on the CVS method, and especially on the drawing a conclusion procedure, so that they could finally "identify the difference between what they know (because someone told them) and what they understand" (Boudreaux et al. 2008).

The *accommodation* was considered to be guided by the educational factor because the refinement's aim was to help students overcome their aforementioned difficulties.

7.3.3 CVS, Changes in the Order of the Focal Variables

Objective In this case, the objective is the same as the previous one. In the first implementation, the variables that possibly affect F/S were tested in the following order: object's shape, object's weight, narrow/wide tank, object's material, kind of liquid.

Resistance According to the researchers' notes, the students found it difficult to understand that differently shaped objects which are made of the same material can have the same weight. The following excerpt from classroom video recordings is indicative:

Teacher: What will be different?
Student A: The shape and weight.
Teacher: The weight. Why?
Student A: Not the weight.
Student B: and the material.
Student A: The material is the same.
Teacher: The material is the same. The shape though, won't it surely be different?
Students: Yes.

Moreover, even though this activity aimed at testing whether the shape of the object affects the F/S, some students claimed that we could draw a conclusion about the object's weight effect on the phenomenon. We think that this difficulty emerged for two reasons: (a) the explanation that weight is responsible for the F/S of an object is one of the most common and powerful alternative ideas of the students (Fassoulopoulos et al. 2003), and (b) when we test whether an object's shape affects its F/S, keeping its volume constant, dependent variables come into the picture (weight, mass, density), which in this age range are usually undifferentiated (Wiser and Smith 2008). In such cases, even older students find it extremely hard to implement the CVS method (Boudreaux et al. 2008).

Accommodation For the above reasons, the order in which we test the variables has been changed. The first variable that was set to be tested is the weight of the object through an experimental demonstration by the teacher. The next two variables (tank's width, kind of liquid), which are tested by the students, are independent of the other possible variables that relate to the phenomenon. Finally, the students have to test two variables (object's material, object's shape).

We assume that in this way, it is easier to understand not only the method's steps (Fig. 4) but also the importance of observation in drawing a conclusion; in other words, to understand the underlying rationale of the method. In short, we propose that when CVS method is introduced to the students, the first variables that the students themselves will test should be independent variables.

The didactical transformation in the framework of this refinement was made in order to help students acquire CVS method and its application as well as the variables that affect F/S, overcoming the aforementioned difficulties. Thus, it was considered that the *accommodation* here was mainly guided by the educational factor.

7.4 Models and Modeling

Six refinements have been recognized concerning models and modeling: (a) the gradual introduction of models, (b) changes in the activity for the generalization of the rule for predicting F/S, (c) emphasis on the same size of the cubes, (d) change in the air cube, (e) change in the way of approaching the technological modeling and (f) emphasis on the difference between a target and its model. The first two refinements are described analytically, while the rest are presented in Table 6.

Table 5 Pickering's model concerning inquiry skills and CVS refinements

Objective	Resistance	Accommodation	Factor	Data sources
7.3.1. Learning elements of CVS	Limited learning of the CVS method	From demo (1 variable (var.)) and guided teaching and learning approach (2 var.) to more open inquiry (2 var.) (gradually)	S[a]	Experts' suggestions Videotaped lessons
7.3.2. Describing the way that we draw a conclusion in the frame of CVS	Students could not describe clearly the way that they proceeded to a conclusion	Explicit emphasis on the drawing a conclusion procedure, with discussion aiming at recognizing the role of evidence	E	Researchers' notes
		Changes in the teaching model that we use for the introduction of the CVS		Videotaped lessons Pre- and post-questionnaires
7.3.3. Describing the way to test a variable using CVS	Students have difficulties in describing the CVS steps when the focal variable is dependent on others	Change in the order of the focal variables that possibly affect F/S phenomena	E	Researchers' notes Videotaped lessons
7.3.4. Describing the way to test a variable using CVS	Students considered six tests needed for the test of each variable instead of two as minimum	Reduction of the number of tests from three to two (the minimum required)	E	Researchers' notes
		Explicit separation of the two phenomena (F/S)		Videotaped lessons
7.3.5. Distinguishing possible logical variables that could affect the F/S phenomenon	Students have difficulties in the distinction between possible logical variables that could affect the F/S phenomenon	Changes in teaching materials of the tasks that aim at the revelation and distinction of the variables that possibly affect F/S phenomena	E	Researchers' notes Teacher's suggestions Videotaped lessons
7.3.6. Searching for and writing down information	Students did not know where to focus during searching for information	Given topics to search for, e.g., environmental consequences	E	Researchers' notes
		From pdf file to simulated Internet website		

[a]*E* Educational, *M* Material, *S* Scientific

Table 6 Pickering's model concerning models and modeling refinements

Objective	Resistance	Accommodation	Factor	Data sources
7.4.1. Learn aspects of nature and the role of models	Limited learning of this content	From a mere model-centered approach to a model-centered approach that emphasizes aspects of the nature and the role of models	E, S[a]	Researchers' notes
		Gradual introduction of models from concrete to more abstract, with discussion aiming at metaconceptual awareness		Pre- and post-questionnaires
7.4.2. Generalize the rule for predicting F/S phenomena	Limited understanding of the role of the same volume of the cube in the *dots-per-cube* visual model of density and the distance between models and reality	The *dots-per-cube* models were replaced by real-looking objects, of different volume and shape	E	Researchers' notes and teachers' suggestions
				Students' Worksheets
7.4.3. Learn the dot crowdedness model, learn aspects of modeling	Difficulty in comprehending what it means to construct a model that would describe the *heavier-lighter* material relation	Emphasize the fact that although the cubes are of the same size/volume they do not have the same weight	E	Researchers' notes
7.4.4. Acquire the concept of density as a property of materials	It strengthened students' idea that air is weightless	The cube of air makes a difference when it is put on the one side of the balance, to indicate the fact that even air has weight	E	Researchers' notes
Construct the object-water *dots-per-cube* rule for predicting F/S phenomena				Videotaped lessons
7.4.5. Solve a technological problem (salvage of a sunken object) using the object-water *dots-per-cube* rule	Students look for the correct solution	Broadening of the concept of correct technological solution under prerequisites (e.g., risk, cost, etc.)	E	Researchers' notes
7.4.6. Pass from the technological to the scientific world	Difficulties in abstracting from concrete situation	Change in the worksheets emphasizing the difference between a target and its model in an F/S phenomenon	E	Researchers' notes
				Students' worksheets

[a]*E* Educational, *M* Material, *S* Scientific

7.4.1 Models, Gradual Introduction of Models

Objective One of the TLS's aims is for the students to understand aspects of the nature and the role of models, using real and simulated environments (see Sect. 4).

Resistance According to the researchers' notes and the results from the pre- and post-questionnaires of the first implementation, only 25 % of the students could write a sentence with the word "model" showing that they understand model as a representation and not as a reality (see task 3, Fig. 6).

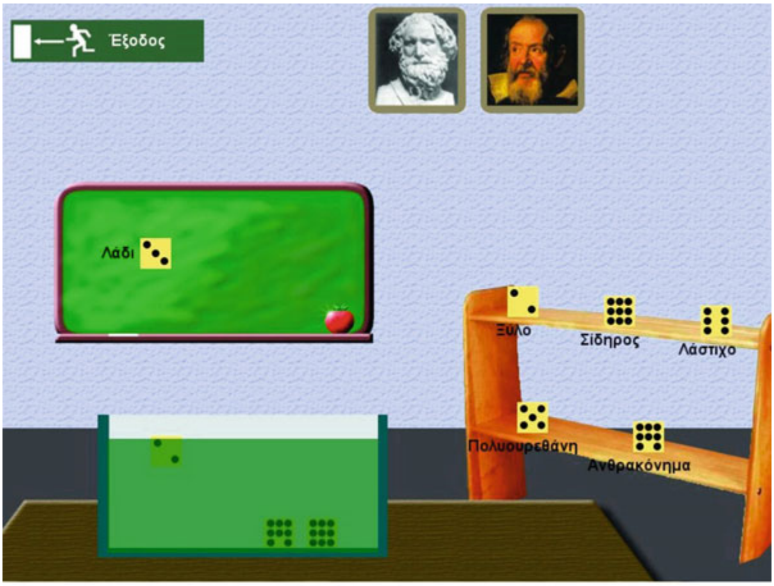
Accommodation In the second implementation, the students used enough of the total given time to discuss the nature and role of models. In addition, there was a gradual introduction to elements of the nature of models. So, in the first unit, the students discussed the nature and role of an object's models (ship models), which are more easily acceptable to students of this age. Next, in the third unit, they discussed the characteristics of the visual models of density, while in the fourth unit, they discussed the causal models that the students presented to explain and/or predict F/S phenomena. In the last unit of the implementation, students carried out discussions about the models that they worked with in the five units, aiming at students' metaconceptual awareness. As shown above, there was a shift to a model-centered approach that focuses on aspects of the nature and role of models (Treagust et al. 2002) – an approach in which the students do not only use models but also talk about them. What is more is that the introduction to models is gradual: from material models to more abstract ones.

We argue that this accommodation was guided mainly by the educational factor because it came up as a response to students' difficulties and, secondarily, by the scientific factor because it was influenced by the scientific literacy demand, which is an element of the inquiry paradigm.

7.4.2 Models, Changes in the Activity for the Generalization of the Rule for Predicting F/S

Objective One of the TLS's aims is the generalization of the object-water *density* criterion (see Sect. 4) to a rule that could cover all liquids. For the achievement of this aim, in the first implementation, the students work in a simulated environment (Fig. 5, Screenshot 1), in which there are *dots-per-cube* models of several materials and a tank with oil. They are asked to propose a way to check if the criterion with which they ended up for the case of water can be applied to other liquids, such as oil.

Resistance According to the researchers' observations, the students found it difficult to propose a way to check the application of the object-water *density* criterion to more liquids. The students just realized all the possible trials they could do, without having any specific strategy in their minds. For example, in the worksheets, one of the groups proposes: "The iron sinks in oil, the carbon fiber sinks in oil, the glycerin sinks in oil, the rubber sinks in oil, the polyurethane sinks in oil, the wood doesn't sink".



Screenshot 1

Screenshot 2

Fig. 5 Change in the simulated environment

Accommodation The abovementioned observations guided us to make several changes in the software, for the second implementation (Fig. 5, Screenshot 2). At first, we replaced the *dots-per-cube* models with more real-looking objects of different volume and shape. For the sake of symmetry, we used glycerin instead of oil, since of the five materials given, only wood floated on oil, while in glycerin, two of them sank and the rest floated. Moreover, apart from the liquid's *dots-per-cube* model on the blackboard (Screenshot 1), students could see and use the five objects' material *dots-per-cube* models as well (Screenshot 2). We thought that these changes would make it easier for the students to understand, on the one hand, the fixed volume of all cubes and, on the other hand, the difference between the world of models (e.g., *dots-per-cube* models on the blackboard) and the world of experiences (e.g., real-looking objects on the shelf).

We argue that the *accommodation* in this case was guided mainly by the educational factor in order to eliminate students' difficulties.

7.5 Indicative Learning Results From the First and the Second Implementations

In order to answer the question concerning whether the refinements were effective, some indicative learning results will be presented. Specifically, the results are from four individual tasks, each one concerning one of the four different content areas of the TLS. The tasks concerning density, models and F/S are included in the written questionnaire, while the task concerning CVS elements understanding is from an interview questionnaire because it was considered to be too difficult a subject for assessment by written questions.

Task 1, which concerns F/S reasoning, was asking the students the change they would make to the system of a ball made of plasticine, being sunk in a tank with water, so that the ball would float on the water. Reference to the comparison of materials' densities or to the material is considered to be the expected learning outcome. In the first implementation, 25 % of the students acquired the expected level of knowledge, while in the second implementation, this increased to 66 % of the students (see Fig. 6). Task 2, which concerns understanding of density as materials' property, was asking students to write a sentence including the words density and material. In this case, the increase was from 41 to 63 % of the students. Task 3, which concerns understanding of models as representations of a target, asked students to write a sentence with the word "model." In this task, there is also an increase from 25 to 56 % of the students. Task 4, which concerns understanding of the draw a conclusion procedure of the CVS, asked students to describe the way that they would come to a conclusion after they had described and hypothetically tested if the shape of an object influences its floating or sinking in a liquid. The students that could adequately describe the procedure of drawing a conclusion also increased in this case from 33 to 64 %. In general, there is an increase in the students who acquired the content which has been taught in the second implementation in comparison to that of the first implementation of TLS.

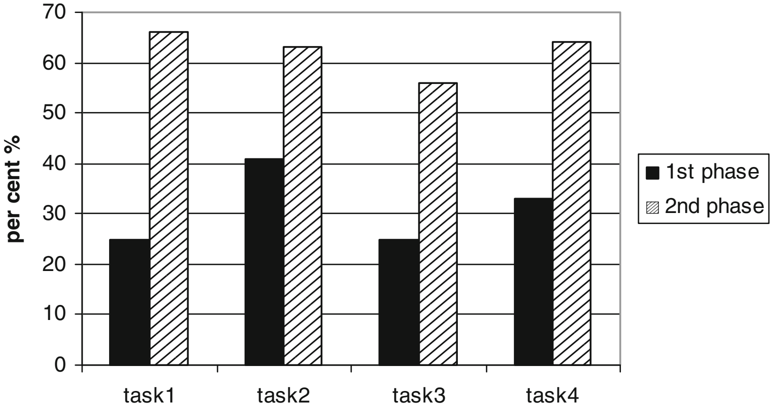


Fig. 6 First and second implementation post results in tasks 1, 2, 3 and 4

Apart from the learning outcomes' results, which indicate the efficiency of the refinements of the TLS, the researchers' notes during the second implementation can also be utilized to enhance this efficiency. According to the researchers' notes, the resistances that appeared during the first implementation were significantly less intense in the second implementation. For example, it is recorded that the discussions in the second implementation that were aiming at the distinction between the concepts of homogeneous and composite objects have helped the students to realize more easily the tasks concerning F/S phenomena of composite objects, i.e., the F/S of a bottle or a ship filled with air or water. Furthermore, both teachers and researchers certify that the students acquired and applied the CVS method more easily due to the gradual degree of *openness* of the inquiry approach. Another example of the success of a refinement is that in the second implementation, the students easily accepted the fact that air has weight, so they could use the cube of air in the same way as with the cubes of other materials, and this was the result of the refinement 7.4.4 presented in Table 6.

8 Discussion and Conclusions

We can discuss the 15 refinements made from the first to the second implementation in four different ways, by changing the criterion according to which they will be described and sorted, answering respectively the four research questions that are described in the research methodology section.

These criteria are (a) the content to which the refinements correspond, (b) the data sources which bring out the need for change, (c) the factor that affected and guided each refinement and (d) the common characteristics among the refinements that are guided from the same Pickering factor.

As we begin to describe and sort the refinements according to criterion (a), we observe that most of them refer to the procedural and epistemological knowledge; six, to the CVS method; and six, to the nature and the role of models. Far fewer are the refinements which concern the conceptual content of science; two, to the interpretation and prediction of F/S; and one, to the understanding of the concept of density. We assume that this happens for two reasons: firstly, because the project's innovative characteristics refer mainly to the emphasis on both epistemological and procedural knowledge, as described in Sects. 3 and 4, and secondly, it is well documented that both teachers (Crawford 2007), even if they are experienced in teaching science, as well as students (Boudreaux et al. 2008; Treagust et al. 2002), find it difficult to adapt to such innovations.

Taking into account criterion (b), i.e., the data sources which bring out the need to change, we observe that most of the refinements were influenced by two or more data sources, enforcing the validity of this analysis in the sense of data triangulation. An interesting finding is that the main data source was the local group researchers' notes (12 out of 15 cases). The researchers' notes are important not only because of their great quantity but also because they refer to the innovative elements of the content, i.e., to the nature and the role of models as well as to the characteristics of the CVS method. In addition, teachers who do not have the experience and the appropriate background could only play a secondary and advisory role (Duit 2007), especially when they are nurtured in a centrally guided educational tradition, as is the case in Greece. This is perhaps the reason that the teachers' intervention in these refinements is limited in two cases (7.1.2 and 7.3.5). Nevertheless, the teachers' contribution was important, since they participated in the evolutionary development of the scenarios and the teaching materials, by commenting on the type and the content of the activities and considering the possibility of them being carried out by the students.

The learning results, as shown in the questionnaires, the worksheets and the video recordings were also important, yet secondary, data sources (11 out of 15 cases). For example, the refinement related to the connection between students' real and simulated experiment interpretations was guided, in a secondary way, by the analysis of students' questionnaires (case 7.1.1).

Experts' suggestions were significant in two out of 15 cases. The small number of refinements is reasonable, considering the nature (advisory) and the function (from a distance) of the experts' role. The first refinement refers to the abovementioned case (7.1.1), while the second refinement refers to the *openness* of the students' inquiry activities (case 7.3.1).

As far as criterion (c) is concerned, i.e., the factor that affected and guided each refinement, we observe that the refinements that are mainly guided by educational factors (E) are 12 out of the 15, while there are two out of the 15 that are mainly guided by educational factors and in parallel, in a secondary though significant way by scientific factors as well (Tables 3, 5 and 6). Although the Greek national curriculum proposes a kind of discovery teaching method, the majority of teachers follow a more traditional teaching method, which is based mainly on the transmission of knowledge, followed by some demonstration experiments. The particular TLS adopts the inquiry teaching method within a constructivist framework. The effort to implement such an innovative project in such a traditional system necessitated many accommodations and modifications, guided by the E factors. Indeed, E factors concern mainly students' difficulties because the students were the researchers' main observation subject. However, the teachers confronted several difficulties as well even though they were assumed to be experienced and well-trained. Teachers' difficulties concerned epistemological and procedural knowledge and especially the nature and role of models, both concerning the necessity of teaching this content and the possibility that the students of this age could acquire this kind of knowledge.

Three out of the 15 refinements were guided by scientific factors (S), one of them in a significant way and the other two in a secondary way. However, these refinements are more essential, and we could call them *pylons*, because they refer to basic design principles of the TLS, influencing all units of the TLS and not only one activity. We also noticed that there are no refinements mainly guided by the material factor (M). We consider that the reason that no refinement was guided by the material factors is that the local group had the appropriate funds. We should also notice that the refinements concern accommodations that relate to (a) the content, (b) the teaching and learning approach of each activity, (c) the materials and the software used or (d) its duration, confirming the relevant literature (Méheut and Psillos 2004). Moreover, the refinements focus both on "inquiry as means" and on "inquiry as ends" (Abd-El-Khalick et al. 2004), through a gradual introduction of concepts and procedures from guided to open (Bybee 2006) and from concrete to abstract (Petrosino 2003).

Considering criterion (d), we notice that there are significant differences between the refinements that were guided by scientific factors (either mainly or secondarily) and those that were guided by educational factors. On the one hand, the refinements guided by scientific factors have a *holistic-open* character while the refinements guided by educational factors have a *local-guided* character.

More specifically, the refinements guided by scientific factors (cases 7.1.1, 7.3.1 and 7.4.1) (a) affect the TLS as a whole, i.e., the accommodation concerns many activities through all five units of the TLS; (b) are relevant to the IBSE (EU 2007) context, i.e., the main researchers' concern is to follow the principles of inquiry paradigm; and (c) promote increasing openness in students' learning methods, i.e., students are expected to construct the expected scientific knowledge through their own intervention and active participation in the learning procedure. Consequently, we call these refinements *holistic-open*, and they could be interpreted by the evolutionary process of acquiring and implementing IBSE teaching and learning methods by the researchers. For example, in case 7.3.1, the accommodation chosen by the researchers was *holistic-open*, in the sense that despite the difficulties the students experienced in understanding and implementing the CVS method, it was decided to select a teaching-learning approach that presents a gradual increase of *openness* to the type and extent of investigation made by the students themselves, following the recent literature trends (NRC 2000; EU 2007).

On the other hand, the refinements guided by educational factors are (a) local and limited to a certain activity of a unit of the TLS, (b) mainly relevant to students' difficulties, (c) guided in the sense that sometimes, there is a specific change in the materials used during the implementation without any change in the openness of students' learning methods, and it is proposed that the new scientific knowledge should be introduced implicitly (cases 7.1.2, 7.3.3, 7.3.4, 7.3.5, 7.4.2, 7.4.4 and 7.4.6), while on other occasions, it is proposed that the new scientific knowledge should be introduced explicitly (cases 7.2.1, 7.3.2, 7.3.6, 7.4.3 and 7.4.5). Consequently, we call these refinements *local-guided (local-guided implicit* and *local-guided explicit)*, and it is expected that they will help students to overcome their difficulties. An example of a *local-guided implicit* refinement is case 7.3.3 where the scientific goal is the learning of elements of the CVS method. The resistance was students' difficulties in applying the CVS steps when the variable is dependent on others. The accommodation chosen to overcome the abovementioned resistance is *local-guided implicit* in the sense that it aims in facilitating implicitly the acquisition of the expected scientific knowledge by the change in the order of the focal variables that possibly affect F/S phenomena. An example of a *local-guided explicit* refinement is case 7.3.2 where the scientific goal is learning the elements of the CVS method. The resistance was students' difficulty in understanding the draw a conclusion procedure. Hence, the accommodation chosen to overcome the above resistance is *local-guided explicit*, in the sense that it aims to make a clear introduction of the rationale hidden behind the CVS method, concerning the role that the observations made during an experiment play in the drawing a conclusion procedure (Fig. 7).

Summarizing the abovementioned discussion, the following suggestions can be made for future extension:

- The refinements are differentiated from each other according to the factors that guide them. The educational factor guides *local-guided* refinements, while the scientific factor guides *holistic–open* refinements, i.e., in the first case, the refinements are necessary in order to deal with the students' educational needs, while in the second, to adjust the TLS to the new scientific trends.
- When one has to design a teaching-learning innovative intervention, very close to the conditions of a regular class and which contains a variety of goals that pertain to scientific content, then a relevant variety of accommodations is necessary. On the contrary, in the case of a teaching-learning intervention with purely research characteristics, being therefore more controllable, the accommodations are usually fewer.

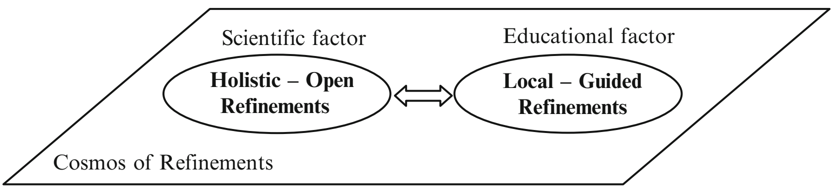


Fig. 7 The differentiation of TLS refinements according to the factors that guide them

- When an innovative intervention is designed and developed in the context of a traditional educational system, then the refinements and proposals for the necessary accommodations, to overcome certain resistances, are made to a greater degree and depth by the researchers. An important role – but to a smaller degree – belongs to teachers and, finally, to the external observers and evaluators.
- During the design and development of this TLS, the research group made an effort to merge, on the one hand, science-oriented tradition characteristics such as paying attention to teaching practice and emphasis on science content issues in designing new TLSs and, on the other hand, student-oriented tradition characteristics such as giving emphasis to the students' needs, interests and learning processes (Duit 2007).

Moreover, although they are not direct results of the present study, the following extension remarks can be made:

- As the design and development of a TLS are not a *one-shot* procedure but an evolutionary process (Méheut and Psillos 2004), several suggestions for refinements could be revealed after the second implementation as well. These refinements concern, however, different subjects from the refinements implemented after the first implementation.
- Although there were several discussions between the teachers and the researchers, we still have doubts as to whether they really agreed to the explicit introduction of the nature and the role of models to primary school students. As a result, teachers' education in relation to the innovative characteristics of the project and especially in relation to the nature and role of models is a crucial point for future programs.
- As revealed from classroom videos and students' interviews analysis, teachers did not adequately emphasize the importance of the fact that the size of the different materials' cubes of the *dot crowdedness* model was the same. That was a key point in order to help students understand the model, and special emphasis should be given to this in the future.

The last two points indicate into a major degree the need for teachers' PCK improvement, in line with a transition from central-guided educational systems to educational systems that give greater initiative to the teacher (Duit 2007).

9 Recommendations

According to the issues discussed in the abovementioned sections, several recommendations can be made for research groups that could possibly begin to carry out similar, developmental type research.

- When a project is innovative, e.g., aiming at introducing new concepts and/or procedures such as nature and role of models and CVS method, especially with primary school children, then a more suitable teaching approach is one that introduces students gradually, i.e., from guided to more open and from the concrete to more abstract, to these new concepts and procedures.

- In the case where the main focus in a TLS's teaching and learning process is (a) inquiry "as ends" and (b) elements of epistemological knowledge such as the nature and role of models in science education, these should be explicitly taught in the form of discrete steps.
- It appeared that the scheme *technological problem – scientific investigation and return to the problem to find a solution*, e.g., through the teaching scenario of the SD's shipwreck salvage – motivates students to study the scientific dimension of a problem in the context of an authentic and real problem-solving situation rather than facing learning as an end in itself.
- Even though the ICT environments are extremely helpful for us to gain time when we apply procedural knowledge in experiments, the connection between the real and simulated experiments is necessary at young ages, in order (a) to avoid the confusion of the real world as we understand it through our experiences, with the model world, and (b) to enhance students' interpretations of real context phenomena in a similar way to simulated ones.

As far as the compilation of a future curriculum for the Greek school is concerned and therefore for any other similar (traditional) one, we could suggest the following: (a) taking as given that students are interested in materials that constitute several new technological products that they deal with in their everyday life, the introduction of materials' science and especially their properties in the curriculum would increase students' interest and participation, and (b) the introduction of difficult scientific concepts, such as density, in a qualitative way, i.e., as materials' properties (wherever this is possible), would decrease the conceptual load for the primary school students.

Last but not least, we consider that an innovation in education needs teachers that are not only adequately educated and trained in relation to the innovative parts of the TLS but persuaded as well concerning the necessity of the existence of these innovative parts in the TLS.

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Design and Development of Teaching-Learning Sequence (TLS) *Materials Around Us*: Description of an Iterative Process

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1 Introduction

The case described in this chapter is *the iterative design and development process of an inquiry-based industry site visit teaching-learning sequence (TLS) – materials around us.* The aim of the chapter is twofold, firstly to describe the design process and justify the decisions that were made within it and, secondly to evaluate the designed TLS from the point of view of students' motivation and interest in science learning and related careers. In addition to that, we will present and discuss what we have learnt about introducing materials science in schools, using an industry site visit as a pedagogical approach.

The aim of the designed TLS was to enhance students' engagement in science and technology (S&T) learning, as it has been proven to be an essential concern within the S&T policy papers of the EU (e.g., EU 2005). This aim has been divided into smaller and more explicit pieces of familiarizing students with materials science topics (the properties and behavior of materials) and careers related to the field in authentic contexts, fulfilling the aims of the curriculum, and supporting students' motivation and interest.

The research literature is approached from two perspectives. First, we examine the literature that concerns the designing of pedagogical interventions. When designing, we engaged in design-based research (Design-Based Research Collective 2003; Juuti and Lavonen 2016, in this volume). Second, we investigated the literature that constitutes the grounds of the design, namely, research concerning student

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motivation and interest, inquiry-based science teaching (IBST), and science learning outside the school context.

1.1 Quality Criteria for a DBR Project

To ensure the quality of design and research in a DBR project, certain aspects need to be taken into account. From the design point of view, the novelty and usefulness of the design solution need to be considered (Edelson 2002), in order to prove the relevance of DBR. The design process is grounded in theory (Edelson 2002, 2006), and the designing takes place as a shared activity of researchers and teachers in order to generate solutions that facilitate more effective ways of teaching and studying (Juuti and Lavonen 2016, in this volume). The iterative design process is carefully documented and formatively evaluated throughout the whole project (Edelson 2006; Design-Based Research Collective 2003), and it leads to a generalizable educational innovation and novel knowledge about aspects of teaching or learning (Edelson 2002, 2006; Juuti and Lavonen 2016, in this volume). In addition to the request of background theory, DBR also takes seriously the considerations of teachers' needs and school practices (Juuti and Lavonen 2016, in this volume).

1.2 Enhancing Motivation and Learning of Materials with an Inquiry-Based Out-of-School Setting

Science education conducted in out-of-school settings has been researched in various contexts, such as museums, science centers, and university laboratories (Griffin 2004; Martin 2004; Falk and Storksdieck 2005; Braund et al. 2008). For example, students' learning, interest and motivation, socialization, and personal development have been researched. According to the synthesis carried out by Braund and Reiss (2004), access to 'real' S&T can have an effect on both learning and interest and motivation. Furthermore, based on a large national survey data set, Lavonen et al. (2006a, b) reported that students would like to increase the number of site visits and the use of visiting experts in teaching. Visiting experts and educational site visits provide an authentic context for learning and facilitate becoming acquainted with applications for scientific knowledge. Through meeting S&T and experts working in the field in an authentic context, students may see the value and relevance of their science studies, and their possible career plans might be given a new perspective.

Meeting scientific concepts in the classroom and in the authentic site visit context can be considered from the point of view of the contextual aspect of learning. Bransford et al. (2000) argue that the learning of new concepts is context bound, and it is more likely that a new concept would become a part of one's knowledge structure if it was introduced in a variety of contexts.

When defining inquiry-based science teaching (IBST), we follow the framework constructed by Minner et al. (2010). They argue that inquiry science instruction has the aspects of *presence of science content; student engagement with science content;*

and *emphasis on student responsibility for learning, students' active thinking*, and *students' motivation*. The last three should take place within at least one of the components of inquiry instruction, which are *formulating the question to be investigated, designing the investigation, collecting and organizing data, drawing conclusions*, and *communicating the investigations*. We enrich the definition with the view of Andersson (2007), as he emphasizes the role of social interaction and collaboration. Traditionally, inquiry activities in science education are organized in a laboratory settings. However, an industry site visit could be organized according to inquiry teaching, with students formulating the question to be answered through interviews and observations, designing the visit, collecting and organizing interview data and observations, drawing conclusions, and communicating the visit outcomes related to materials science content.

Interest motivates people to learn (Silvia 2008; Deci 1992). Thus, from the educational perspective, the challenge is to get students interested. Interest is always content-specific, and it is aroused as a function of the *interestingness* of the event or object (see Schraw et al. 2001). It may be partially under the control of the teachers, by means of organizing interesting learning environments. According to Silvia (2008), the appraisal of the *novelty and complexity* and the appraisal of the *comprehensibility* of an event are crucial in order to get interested in it. Palmer (2009) adds learning, choice, physical activity, and social involvement in the list of aspects that have an effect on situational interest. If successfully caught and maintained long enough, spontaneous situational interest may turn into more permanent individual interest (Krapp 2007; Hidi and Renninger 2006) that may be related to an individual's feelings or values (Schiefele 1999).

Motivation, in general, refers to the process of generation and maintenance of goal-directed activities (Schunk et al. 2007). In this research, motivation has been examined in the light of the Self-Determination Theory (SDT) (Deci and Ryan 1985, 2004, 2008), which distinguished different quality types of motivation. According to SDT, motivated behavior may be *autonomous*, which means behaving with a full sense of volition leading to good-quality learning outcomes, or *controlled*, which involves engaging in an activity because of its consequences, or motivation may be absent, in which case the person's motivation orientation is said to be *amotivation* (Deci and Ryan 2008). Autonomous motivation exists when people's basic psychological needs are satisfied; these are, according to Deci and Ryan (2004), the need for autonomy, the need for competence, and the need for social relatedness (the need to belong to a group).

In order to understand Finnish students' interest in science and science-related careers in more detail, two large surveys were conducted in Finland before this project (for details, see Lavonen et al. 2008a, b). According to these surveys, for example, choosing contexts emphasizing societal issues in science education, choosing teaching methods to help students become familiar with the use of science in society, and demonstrating the characteristics of occupations may increase students' interest in science and science-related occupations.

We argue that the designed TLS fulfils the criteria of inquiry-based science teaching; has the potential to enhance students' engagement; and, furthermore, brings together out-of-school learning and learning in the classroom in a manner that benefits both. Meeting materials science content both at school and in a new and authentic context helps the students to deepen their understanding about the science-related concepts they will meet during the visit (Astin et al. 2002).

2 Context: Finnish Science Education Context

One of the main characteristics of Finnish education policy is the devolution of decision-making powers to the local level. According to this principle, schools and teachers are responsible for choosing learning materials and teaching methods. They are also responsible for evaluation policy since there are no national examinations in compulsory education. These characteristics of education policy are supported through a flexible national level curriculum and master's level teacher education. In the National Core Curriculum (NCCBE 2004), general goals, subject-specific goals, and basic concepts in each subject are briefly described. In lower secondary school (grades 7–9), science is divided into the separate subjects of physics, chemistry, biology, geography, and health education, all taught by highly specialized subject teachers.

Based on the Finnish PISA 2006 Scientific Literacy Assessment data, the teaching methods and learning materials in Finland are rather traditional and emphasize a combination of teacher-delivered instructions and demonstrations and student-conducted experiments (Lavonen and Laaksonen 2009).

3 Designing a TLS on the Properties of Materials

The starting point of the design process was updating the model for an activity-based industrial site visit (Kuitunen and Meisalo 1988) to fit in with the materials science context and to include motivation and interest supporting features, based on the literature. The model emphasizes student activity, in contrast to traditional sightseeing-tour visits. It was introduced in the 1980s, but it was not widely employed. Besides the materials science content and the motivation and interest promoting features, the use of ICT in the acquisition of information and inquiry orientation is different from what was introduced in the original version of the model.

When designing the prototype for this project, experiences gathered during several science teachers' professional development projects (Juuti et al. 2009; Lavonen et al. 2004, 2006a, b) have been utilized. Furthermore, we have applied the principles of pragmatic DBR as described by Juuti and Lavonen (2016, in this volume), and designing the TLS has been conducted in collaboration with teachers. Their views, beliefs, and habits have seriously been taken into account. In practice, we emphasized reflective discussions with teachers while developing the TLS. The core challenge when designing the TLS has been implementing the aim to design teaching-learning TLS that could be used at any school in Finland or even elsewhere in Europe, despite the location of school or number of students in the class.

We concluded from our literature review that student motivation and interest may be promoted through selecting activities that support students' feeling of competency, social relatedness, autonomy, and interest towards S&T. We argue that the TLS with inquiry activities and industry site visit encompasses many such features. The TLS may awaken students' interest through offering them novel experiences and multi-faceted and even surprising phenomena to see in an authentic context and introducing them to career possibilities in the field of S&T. We understand that situational interest is difficult to measure, and in the interview, students may not be able to retrospectively track the aspects of the situation that really caught their interest. However, we know based on the literature review what aspects of a topic or a situation appeal to the situational interest of people, and we designed the TLS not only keeping in mind aspects that may have this appeal but also considering possibilities to meet the students' personal interests.

Because study visits are recommended in the National Core Curriculum, visits are organized at schools even without our TLS. However, there are distinctions between this TLS and ordinary study visits. The TLS we designed has a structured wholeness that encompasses preparation, visit, and elaboration afterwards. The philosophy of IBST actualizes in the students' role, as they actively plan the data gathering, gather the data, and process them afterwards. The integrative approach between science and mother tongue gives a special characteristic to this project. Also the conceptualization of the means that may help to enhance students' motivation distinguishes this project from TLS projects.

3.1 Materials Science Content

The TLS supports students' learning about the *nature of materials science and technology*, as students become familiar with how new innovations are refined into products in authentic environments through technological processes. Students also familiarize themselves with the *methods of materials science* by learning how research and development concerning materials science issues is done with modeling and simulations, using high-technology appliances. Moreover, students learn new *materials science* content, materials science terminology, physical and chemical properties, and the production and use of materials. They get acquainted with how the behavior of materials can be explained by analyzing their structures and how microscopic models describe the properties and behavior of materials. The structure of matter is one of the most fundamental topics in science, and a meaningful understanding about this topic is essential for developing a solid basis for further science studies, and therefore, students take a deep look at models which describe the structure, properties, and behavior of materials. Finally, students learn about *careers in material science and technology* in the site visits, as they meet scientists, engineers, and many types of professionals in modern materials science enterprises and laboratories. This helps them to see their possible career options from a new perspective.

The significant scientific concepts and phenomena examined within the TLS are raw material, material, substance, phase, physical properties and chemical properties (e.g., heat conductivity, electrical conductivity), particle, monomer, thermoplastic polymer, thermosetting plastic, etc. The processes students get acquainted with are manufacturing iron from iron ore, manufacturing paper from wood, and manufacturing different plastic qualities from raw oil. Furthermore, students familiarized themselves with the properties and structure of materials by employing microscopic and submicron level models.

4 Development and Refinement of the TLS

The prototype of the TLS was designed using the design principles. The outline of the pilot version is presented below. The structure of the prototype is based on the model of Kuitunen and Meisalo (1988) (Table 1).

After the cycles of designing and re-designing, the TLS was finalized. The iterative process through which the pilot version was converted into the final one and the decisions that were made during the process and their justifications based on the

Table 1 Structure of the pilot site visit sequence

Phase	Activity	Theoretical justifications
1. Advance planning by teachers	General level planning by science teacher and career counsellor	
2. Preparatory visit by the teacher	Teacher plans the visit with the company contact person	
3. Students' preparation	Co-planning the visit	Co-planning supports student autonomy
	Formulating study groups, learning about the company by using web resources, formulating questions, and sending them to the company. ICT is used in this phase	Collaborative and student-centered activities support student autonomy, competence and relatedness
4. The site visit	Introduction and sightseeing	Collaborative and student-centered activities support student autonomy, competence, and relatedness
5. Students' group reports	Students prepare and present the reports. ICT is used in this phase	Collaborative and student-centered activities support student autonomy, competence, and relatedness
6. Feedback with the site representatives, evaluation of the reports		Evaluation and informal discussions help students recognize their strengths and increase their feeling of competence
7. Collecting ideas for future visits		

analyzed data are described in more detail in Sect. 7.4. A detailed view to the TLS with concrete instructions for all its phases is offered in the Student Book (Lavonen et al. 2009a, b) and the Teacher Guide (Loukomies et al. 2009a, b). During the design-research project, the aims of the TLS were formulated as follows in collaboration with the teachers. The Materials Around Us TLS aims to help students become familiar with everyday materials, like metals, plastics, and paper in everyday contexts and in their production or commercial uses. The properties and behavior of common materials, the use of these materials, microscopic models describing the properties, and behavior of materials, and, moreover, the usage of (raw) materials in constructions and in manufacturing products are introduced to students. In order to facilitate constructing a holistic view of materials, modern technology, and careers in this field, different kinds of learning activities are used, and the topic has been approached from the perspectives of different school subjects. In more detail, career counselling, learning activities typical of science learning, and learning activities typical of mother tongue are combined within the TLS.

The structure of the final version is presented below. Instead of the seven phases of the pilot version, there are three main stages in the final version, namely, preparation, site visit, and follow-up activities. The major difference compared with the pilot version is that all the tasks are more structured and the wholeness is more tightly organized, and the responsibilities of the participants are explicated. The teacher is given more detailed information about how to proceed in certain phases. However, the structure is flexible enough to be implemented with a variety of companies (Table 2).

In the final version, students' feelings of autonomy are supported through collaborative planning and allowing the students to make decisions about their data collection and article writing, group formulation, information searching strategies, and conducting the inquiry tasks. Students' feelings of social relatedness are supported through collaborating with peers and having informal discussions between the teacher and the students. Students' feelings of competence are supported by offering them constructive feedback and help alongside the process of gathering data and elaborating it in the article writing task and in the evaluation discussions. The interesting context is built into the procedure in the form of site visit.

5 Implementations of the TLS

All teachers organized site visits according to the principles of the TLS, with more scaffolding from the researcher team in cycles 1 and 2 and more independently in the final cycle. Even though there were a variety of companies that the students visited, all visits took place in materials science contexts, and the same materials science-related inquiry activities were employed in all of the implementation, and furthermore, compared with ordinary site visits, emphasis was on the preparation-visit-elaboration structure and instructional methods that supported students' motivation and interest. In cycles 1 and 2, all refinements had not taken place yet.

Table 2 Structure of the final version of the TLS

Phase	Student activity	Teacher's task
1. *Planning and preparation*	Six optional *inquiry tasks* about the properties and use of materials and models that describe the structure of the materials (paper products, plastics and metals)	*Planning the organization* of the visit with the company contact person and career counsellor
	Searching for information over the Internet about the company and finding out about its production of materials	*Planning the writing task* in collaboration with the mother tongue teacher. Mother tongue teacher teaches the article as a text type and introduces the data gathering methods
	Deciding about the *perspective of the article* (follow-up reporting activity). Examples:	*Helping* students with focusing on the topic of the article
	Materials used in the company's production	*Introducing* the inquiry tasks and working methods; guiding the activities but letting the students organize their working
	Raw materials and their origins	*Organizing* the ICT-based information searching
	Different occupations and education needed for these occupations	*Organizing* the connection with the company
	Planning the relevant *interview questions* for gathering data to the writing task	
	Sending the questions to the company	
	Becoming familiar with the *work of journalists* and means of data gathering	
	Studying *article as a text type*	
2. *The site visit*	Students in a role: *investigative journalist*	*Organizing* the practical aspects related to the visit
	Introduction to the activities of the company, *presentation*	*Guiding* students during the visit
	Manufacturing processes	*Helping* with the data collection
	Economic aspects	
	Environmental aspects	
	Careers and occupations	
	Interactive *sightseeing* tour, students in small groups	
	Data collection for the articles by conducting short interviews; *interviewing* the personnel members, in small groups	
	During the site visit, the students take notes about what they see and hear.	
3. *Follow-up activities*	Collaborative *article writing*	*Guiding* the writing process, offering feedback and suggestions
	Evaluation discussions and evaluation *questionnaires* (see the Student Book)	*Organizing* the article's publishing
	Feedback is sent to the contact person of the company.	*Collecting* students' opinions
		Sending feedback to the company

5.1 Pilot Cycle: Okmetic Plc

As a pilot cycle of the design, the prototype was tested in a site visit to the materials science in the industry plant Okmetic Plc. Okmetic produces silicon wafers for various technological purposes. Ninth-grade students (N = 21) from a suburban comprehensive school (Northern Helsinki, Finland) participated in the visit.

5.2 First Cycle: Vaisala Plc

In the first cycle of the design process, eight-grade students (N = 14) from a suburban comprehensive school (Eastern Helsinki, Finland) visited the company Vaisala Plc, which has been profiled as one of the global leaders in environmental and industrial measurement, providing observation and measurement products and services for meteorology, weather critical operations, and controlled environments.

The design process started with a planning meeting, which the researcher team, the science teacher, and the career counsellor attended. It seemed that in the pilot cycle, students had difficulties in finding the connection between their science studies and the visit, and as an outcome of the reflective discussions about the experiences of the visit, it was decided to include materials science-related contents in the preparing phase. Students conducted experimental tasks related to the physical and chemical properties of materials. One example was covering coins with another metal, in which a 'copper' coin was plated with zinc in a solution of sodium zincate and appeared silver in color. Then the plated coin was held in a flame for a few seconds, and the zinc and copper formed an alloy of brass; this gave the coin a golden color. The instruction of the task was structured by the teacher.

The intention was to familiarize the students with the professions and products of Vaisala Plc in order to enable them to see science, technology, and different materials applied in an authentic context. The students prepared themselves by examining the company's web site and by drawing up interview questions. In order to enhance students' responsibility for their own learning, they were told that their output was to be a report about a certain aspect of the visit, written in pairs or small groups.

During the visit, students were shown a presentation and an exhibition about the company and its products and how different materials were utilized in them. At the end of the visit, students released a radiosonde in the yard and followed it on a computer screen. During the visit, the students took notes about what they saw and heard. They also interviewed persons who had relevant information for their reports. After the visit, the students completed their texts and the teacher compiled them into a booklet. There were no specific requirements for the style and structure of the reports.

5.3 Second Cycle: Metso Automation Plc

In the second cycle of the design process, ninth-grade students (N = 15) from a suburban comprehensive school (Eastern Helsinki, Finland) visited the company Metso Automation Plc. Metso is a global supplier of technology and services for the mining, construction, power generation, oil and gas, recycling, and the pulp and paper industries. The second cycle of designing and testing the site visit TLS started with a planning meeting that the researcher team, science teacher, mother tongue teacher, and career counsellor attended. The structure of the TLS was revised from the seven-phase model of the pilot cycle to a three-phase model that consisted of preparation, visit, and follow-up activities. This way, the structure was clearer. A combination of materials science contents was included in the preparation phase of the second cycle in the form of inquiry activities. Plastic, paper, and metal were chosen to be the materials for students to examine. It was decided that this time, the students' output would be an article related to the visit. Special emphasis was decided to be put on the writing process and studying articles as a text type. This aim generated a natural means of integrating the science and mother tongue curricula. Before the visit, the students familiarized themselves with the company's web site; decided on the viewpoint of their articles; drew up questions they would ask the employees; and conducted inquiry tasks related to paper, plastic, and metal, as well as their structures. The aim of the visit was to familiarize the students with S&T-related professions and show them how the materials they had examined within inquiry activities were applied in an industrial context. With the help of the mother tongue teacher, the students collaboratively wrote articles about certain aspects of the visit. Compared with the previous cycle, the instructions for the article task were planned in collaboration with the mother tongue teacher. The mother tongue teacher also took responsibility for introducing the students to articles as a text type and allocated mother tongue lessons to guide the students' writing processes. The students' questions were also prepared, keeping the writing task in mind. In brief, the post-visit writing task was far more organized and more tightly instructed compared with the previous cycle.

During the visit, the students were shown a presentation about the company and its products and how different materials were utilized in the products. The students made notes about what they saw and heard. They also interviewed persons who were experts in the topic of their articles. The teacher guide and the student book *Materials around Us* were prepared based on the experiences gathered over two cycles.

5.4 Final Trial

After finalizing the student and teacher material, it was introduced to six lower secondary school science teachers from the surroundings of Helsinki, Finland. The teachers participated in a 2-day professional development meeting, in which they were presented different approaches to everyday materials, and they were given ideas for how these materials could be taught to the students. There were altogether

110 students in the teachers' groups who participated in the course. Participant teachers familiarized themselves with the TLS, and researchers and teachers then came to a shared understanding of the essential aspects of the TLS, in more detail, the means of enhancing motivation and interest, inquiry-based science teaching, and organizing industry site visits. The teachers tried the inquiry tasks included in the procedure themselves, and they had time to plan their own site visits. In addition, the teachers and researchers planned collaboratively the implementations of the TLS for every teacher, because the teachers were about to visit different companies. The meetings were collaborative and emphasized the dialogue between researchers and teachers. After the course, the teachers organized site visits and related activities independently without the strict guidance of the researcher team. A reflective meeting was organized 6 weeks after the course. In this meeting, teachers were interviewed about their experiences of using site visits as a way of teaching science. The interview was a loosely structured reflective group discussion around the same themes as the student interview. Because the researchers did not attend these visits, the group interview was an important means of gathering information.

6 Research Questions and Methods

6.1 Research Questions

The aims of designing and refining the TLS and enhancing students' motivation and interest in science learning and related aspects are intertwined, because information about the fulfilment of the TLS aims also offered information about the successfulness of the operationalization of the theoretical constructs and, furthermore, the design *per se*. The formulation of the research questions not only clarifies the distinction between the two levels of the research aims but also generates a synthesis for the evaluation of the design process. To sum up, the research questions are as follows:

1. How was the TLS designed and revised during an iterative process?
2. How were the changes and decisions in the design justified?
3. What did the *Evaluation of Science Inquiry Activities* Questionnaire (ESIAQ) and student interviews reveal about motivation and interest-related aspects of the TLS?

Research questions 1 and 2 are answered on the basis of the formative evaluation that took place during the project, e.g., feedback of external evaluators and participant teachers. Research question 3 was answered by analyzing students' interviews.

6.2 Data Collection

The empirical data encompass the experiences and views of students, teachers, and external evaluators. Data collection methods can be seen as a means of formative evaluation, and the data were analyzed not only within the project but also

Table 3 Data collection methods during the cycles

Cycle	Data
Pilot cycle, Okmetic Plc, 2007	Students' evaluation questionnaire, Likert scale (N = 21)
	Students' evaluation questionnaire, open questions (N = 21)
	Video recordings of the planning phase and the visit
First cycle, Vaisala Plc, 2008	Video recordings of the planning phase and the visit
	ESIAQ (N = 14)
	AMQ (N = 14)
	Interview of the teacher
	Interview of the students (N = 4)
	External experts' evaluation
Second cycle, Metso Automation Plc, 2008	Video recordings of the planning phase and the visit
	ESIAQ (N = 15)
	AMQ (N = 15)
	Interview of the students (N = 4)
	Interview of the teacher
Final trial, 2009	Group interview of the teachers

retrospectively. The conclusions, which emerged from the analysis of the data and evaluations of the process, have been prescriptive when making decisions about the re-designing. We have conducted a pilot test, two different cycles of design, implementation and refinement, and a final trial. In order to answer the research questions, several sets of data were collected during the design process, using multiple sources of evidence (video recordings, student and teacher interviews, meeting memorandums, and questionnaires) according to the principles of case study research (Yin 1994). Data from a certain cycle have been collected and analyzed before moving to the next one. Table 1 describes the data collection methods employed during the designing and testing activities. Analysis of the data has mainly been theory driven. The students came from different schools in all the cycles (Table 3).

Evaluation of Science Inquiry Activities Questionnaire *(ESIAQ)*[1] (Appendix 1) assesses participants' subjective experience related to a target activity. In the Finnish translation, target activity in the before-visit-questionnaire was described as the students' hands-on activities they conducted within their science lessons. After the site visit, the target activity was the TLS. The instrument assessed participants' interest/enjoyment (seven items), perceived competence (six items), value/usefulness (seven items), and perceived choice (seven items). A seventh subscale, relatedness (six items), has been recently added. The *ESIAQ* uses a seven-point Likert-type scale (1 = item in my case is not at all true… 7 = item in my case is very true).

[1] *ESIAQ* is based on Intrinsic Motivation Inventory (IMI), http://www.psych.rochester.edu/SDT/measures/intrins.html

The students' SDT-based motivation orientations were examined with the Academic Motivation Questionnaire (AMQ)[2] (Appendix 2). The results of the analysis of AMQ data and the implications for science education practice are discussed in detail in the paper of Loukomies et al. (2013). The interview was used to examine the students' engagement and experienced learning outcomes when employing the industry site visit as an instructional method (Appendix 3). The teachers (N = 2) from cycles 1 and 2 were also interviewed about their experiences. They were asked to explain their views of the student engagement. The perspective was teachers' observations and feelings about their students' behavior and actions and how it differed from what was usual. After the final trial, six participating teachers were interviewed with a similar protocol as in the previous cycles.

The interview protocol was developed based on the literature review on motivation and interest. There was also a second part in the student interview that concerned students' conceptual change within the module. The interview questions of this part concerned material met during the visit, products that were manufactured of these materials, and careers and professions that were related to the company. The results of that part are discussed in other papers due to the extensiveness of the topic. The aim of the interview was to clarify the features of the module that supported students' motivation and interest through supporting their possibility to choose or their feelings of autonomy, their feelings of competency, social relatedness, and the development of interest.

6.3 Data Analysis

From the point of view of the scope of this chapter, the most significant data are those from the external evaluators', students', and teachers' statements that are related to the problematic, irrelevant, and incoherent aspects of the TLS and, furthermore, the suggestions for amendments. The external evaluators' statements were collected into a document that was considered in the teacher-researcher meetings. During these meetings, problematic aspects were discussed one at a time, keeping the relevant literature in mind, and new procedures were generated. The memoranda of the meetings, which took place within different cycles, are collected in the research log.

Data from *ESIAQ* were analyzed by comparing the means of students' answers before and after the TLS with *t*-tests. Students were categorized on the grounds of their SDT-based motivation orientations by K-means cluster analyses of the AMQ, and representatives of each category (amotivation, controlled and autonomous motivation) were then chosen for semi-structured interviews.

The interviews took from 20 to 29 min, and they generated 8–13 pages of transcripts each. The first half of the interviews concerned motivation, and the other part

[2] AMQ is based on the Academic Self-Regulation Questionnaire (SRQ-A) and Academic Motivation Scale (AMA), http://www.psych.rochester.edu/SDT/measures/intrins.html.

concerned students learning. A table for analyzing the interviews was constructed based on self-determination and interest theories, and it followed the grouping and themes of the interview questions, so the analysis followed the principles of theory-driven content analysis (Patton 2002). Four main categories for students' comments were autonomy-supporting activities or support for choices (AU), support for students' feeling of competency (CO), support for students' social relatedness (SR), and support for interest (IN). One researcher read the students' answers several times. First, the interviewees' utterances were associated with the four features mentioned above. Second, reduced expressions in English were composed after distinguishing the relevant issues from the ones focusing on something else and encoded with the relevant category code in the analysis table.

Students' word-for-word quotations, the English translations of the word-for-word quotations, and the coded reduced expressions of these quotations were arranged in the analysis table. This way, it was possible to find out which motivational features of a task were important to students with different motivation orientations.

7 Results

In this section, the results of the data analysis are discussed insofar as they offer information about applying the motivation and interest research and have an influence on the TLS design decisions. The results concerning individual students' learning, motivation, and interest are discussed elsewhere. In Sect. 7.5, we discuss in detail how the results influenced and re-directed the design process.

7.1 Results of Teachers' Interviews

In this section, we examine the results of the teachers' interviews from cycles 1 and 2 and the final trial. We examined what motivational aspects of the TLS arose from the interviews. The following aspects most commonly emerged from the teachers' interviews. Firstly teachers found that the students' feelings of autonomy were supported in the preparing phase (inventing questions and getting familiar with the company's web site), when organizing the groups and in the phase during which inquiry tasks were conducted. The students engaged in the inquiry tasks and worked intensively; they worked autonomously with ease, and the teachers considered that it was just the feelings of autonomy and freedom that engaged the students in the task. As the interviewed teachers put it, 'the inquiry tasks were done more independently, and that might have been the reason why they liked them,' 'it was just that they weren't too guided and students got to proceed independently,' and 'it might have been that in the visit the questioning occasion that no one wanted to know beforehand how things were done so it was a full autonomy.' However, in some cases, the teacher organized the groups and the tasks so that there was something to do for all the group members in all the groups. In other cases, the teacher let the students decide about the groups and the work schedule, 'they mainly got to decide themselves about what kind of groups they were about to proceed.'

All the interviewed teachers supported their students' feelings of social relatedness by encouraging them to work in groups; some teachers even let the students organize the groups themselves. '[T]hen in the writing phase they benefitted from each other, … they did the tasks in small groups independently… Teachers also found there were aspects in the procedure that supported students' feelings of competence. The inquiry tasks were at an appropriate level for the students, and that promoted their feelings of competence.… they were nicer than usual inquiry tasks as they were given independence and the tasks weren't too difficult,… it was very well at students' level and they got interested.

The fact that students' articles were to be published made the students think they needed to complete them with care. The teachers emphasized the significance of getting the students prepared well. Students' pre-existing knowledge and their possibility to discuss with adults working at the site seemed to support their motivation and interest in the site visit. They also liked doing the pre-work and then, when there was the mother-tongue teacher involved, brought something like how important it was that when the report was about to be written, it had to be done properly when the mother tongue teacher also read it; it was valuable for them that they were treated [on the site] like real people.

The interviewed teachers mentioned aspects that concerned both students' feelings and values. They mentioned it was important that the representatives of the company spoke about issues and curiosities that caught the students' interest. The students were particularly attentive when the employees of the companies spoke about their own jobs and what they involved. The site visit also gave the students a perspective about what technology-related occupations are like and what career possibilities there are in this field. The possibility to have refreshments enhanced positive feelings towards the visit. Teachers said that 'the most important thing influencing enjoyment was the refreshments but I think the most important was that it is not the career counsellor or me who is speaking about the issues and professions but someone that really does the work,' 'that they got to send the weather balloons themselves and then really saw what the function of the balloon was and what kind of preparation was needed, it was really interesting, and the students' enthusiasm was the most important thing I remember', 'the person who was speaking to students was very interesting, and he had had the ability to speak so that he took the students' worlds into account,' 'a student of this age gets interested if he gets where things really happen.'

Even those students who were in a somewhat prejudiced mood before the visit seemed to have enjoyed the visit. The students liked the environment, meeting people who worked in the field, hands-on tasks, and the interesting exhibitions they saw. The interviewed teachers also mentioned some aspects that concern the practical arrangements of the visit. They found the TLS a natural way for interdisciplinary collaboration with their colleagues, from which all participants could benefit somehow. On the other hand, they considered the TLS quite time consuming. They experienced difficulties in including the TLS in their schedules and organizing the practical issues with their colleagues. These issues may prevent teachers from organizing other TLS projects. In the first cycle, the teacher involved felt that she had to do the quite challenging organizing tasks all by herself.

7.2 Results of the ESIAQ

The results of the ESIAQ from cycles 1 and 2 are presented in Table 2. The questions are categorized into subscales based on the SDT. Means before and after the implementation (M_1 and M_2) and standard deviations before and after ($S.D_1$and$S.D_2$) are presented for each category. The results for the *t-test* are in the outermost right column; they show no statistically significant difference for any of the categories. The reasons for this are considered in the Discussion section (Table 4).

Table 4 Means, standard deviations, and *t*-tests for motivation subscales based on students' evaluations in first and second cycles

Design cycle	Motivational features of the science activities in general and MS TLS activities	Science activities in general			TLS activities			
		N	M_1	$S.D._1$	M_2	$S.D._2$	$M_2–M_1$	t
1st	Perceived autonomy/choice[a]	12	4.20	0.66	4.12	1.00	–0.08	–0.389
	Perceived competence[b]	12	4.42	0.90	4.90	0.79	0.48	2.386
	Support for relatedness[c]	12	4.89	1.39	4.85	1.02	–0.04	–0.264
	Interest/enjoyment[d]	12	4.07	1.14	4.20	1.30	0.13	0.438
	Interest/value or usefulness[e]	12	4.77	1.32	4.74	1.54	–0.03	–0.153
2nd	Perceived autonomy/choice[a]	15	4.94	1.37	4.30	1.20	–0.64	–1.897
	Perceived competence[b]	15	4.76	1.46	4.42	0.74	–0.34	–1.369
	Support for relatedness[c]	15	4.54	0.81	4.20	0.58	–0.34	–1.485
	Interest/enjoyment[d]	15	4.73	1.29	4.40	0.73	–0.33	–2.186
	Interest/value or usefulness[e]	15	5.32	1.71	4.63	1.55	–0.69	–1.288

All mean differences in the table are non-significant
Examples of items in each subscale
[a]I do the activity because I want to do it
[b]I think I am pretty good at the activity
[c]I feel close to my peers during the activity
[d]I enjoy the activity very much
[e]I think doing the activity could help me to learn science

7.3 Results from Students Interviews

The Self-Determination Theory of motivation categorizes different motivation orientations. We applied this categorization by employing the AMQ questionnaire and a cluster analysis of it and grouped the students into three motivational categories based on the questionnaire data. Representatives from all the motivation orientation categories were interviewed. The interviews were analyzed one cycle at a time. The following aspects indicating that, of those parts, the designed motivational features had met the students' needs, arose from the students' interviews in both cycles. They were considered remarkable when refining the TLS, and therefore, they were emphasized in the final version of the TLS.

The significance of working in groups, meeting the authentic context, and real-life applications of science arose from the answers of the amotivated students. One student said, 'well because when all the people have like different opinions about issues of what they prefer, and then when you combine them then it will be one big surprise box or such a thing from which you get all kinds of bursts of motivation and so on… especially that of course there are like friends and familiar people, so that made it easier, but also that when you study it kind of felt more effective because you had a good group so you also shared the aims and so on.' Students with controlled motivation mentioned among others the possibility to break the everyday routines, the significance of the company of their classmates, and an interesting new context for studying. Finally, students with autonomous motivation mentioned the possibilities to learn new things during the visit, meeting real people working in the field of S&T, and possibilities to choose and work in a group. One student described this as follows: 'well in principle when you had the kind of feeling that the tasks weren't just put in front of you and you just have to do them, but that you had the possibility to influence what you are about to do so that….' In general, students, despite their motivation orientation, emphasized the significance of collaborating with peers and the authentic context. In what follows, there are two examples of this: 'well mm when you got there so I did realize that yes like this is quite nice probably to study if there are this kind of issues related to it… before this [the visit]… for me it was important only to have paper in the store so that I could draw and so on but then when you start to think about the fact that there are so many phases when they do things, so of course it is interesting how they manage and how it is done, what are the processes.'

7.4 External Evaluators Comments

In the first cycle, the external evaluators wrote a report about their reflections of the site visit. They criticized the missing link between the chemistry lessons and especially the concepts taught in them and the site visit. The external experts argued that the site visit was a detached factor only appealing to the affective domain of students' interest towards science and not connected with studying science. They were also critical of the teacher being left alone, without support from the researcher team.

7.5 Re-design Decisions

In this section, the design process is reflected one cycle at a time. Problematic aspects that emerged from the reflective teacher-researcher discussions, student and teacher interviews, and external experts' comments are explicated. There is a table at the end of the description for each cycle, summing up the major problematic aspects and the decisions about changing the weaknesses and inconsistencies in the procedure.

After the pilot cycle, the students felt very positive about the site visit in general, and they were willing to take part in other similar visits. They reported that they had learnt about how science can be applied in a real-life setting and what kinds of occupations and careers there are in the field of S&T.

However, they did not learn so much about pure physics and chemistry during the visit in their own opinion. This was an issue to be corrected, as it is very important to connect the visit to the curriculum. It was decided in the teacher-researcher meeting that some materials science-related inquiry tasks should be added in the preparation phase. This would help the students see the science content during the visit and meet materials and their properties in various contexts. Furthermore, the company personnel should be informed about the level of students' existing knowledge in order to be able to speak at an appropriate level for the students. The students were not very interested in the reporting task in the pilot cycle. It was decided that clear instructions should be given for writing the reports and that students' reports would be published on the school's website (Table 5).

In the first cycle, the students were interested in studying in an authentic context. In the interviews, they mentioned having been excited about the attractive role models, seeing how physics and chemistry were applied and the device they saw during the visit. The students also enjoyed working in groups. However, despite the inquiry

Table 5 Problematic aspects and decisions associated with changes in the pilot cycle

Pilot cycle	Problematic aspects	Data source	Decision about change
2007	Lack of science content	Students' evaluation sheets	Examining pre-existing knowledge
			Inquiry tasks to introduce the content to students
	Lack of motivation in the reporting task	Students' evaluation sheets	Structured reporting, the publishing of reports
	Too complicated science content in the visit	Students' evaluation sheets	Clarifying discussions with the contact person of the company

activities conducted beforehand, the external evaluators were critical about there being too few links between the visit and the study of science in the classroom. Moreover, in the teacher's opinion, the cooperation between her and the researchers was incoherent, and the teacher did not get all the support she needed.

After this evaluation, the problem of connecting the visit to the curriculum was taken into consideration again. More science content materials were included in the procedure in the form of inquiry activities that also support the students' feelings of autonomy and peer collaboration. Students' autonomy was supported by generating such task instructions that the students could follow without direct guidance from the teacher. The students were given the opportunity to choose between various options, for example, allocating the tasks to groups. Students' collaboration and social relatedness were supported by letting them work in groups. All group members were needed in order to succeed with the experiment, and the students were encouraged to reach the explanations for the experiments in collaborative discussions. The researchers and the teacher who participated the second cycle designed the inquiry instructions collaboratively.

Teacher-researcher collaboration and expertise of a mother tongue teacher were employed when designing instructions for the reporting phase. It was decided that students should work as investigative journalists during the visit; they could autonomously decide on the scope of their article according to their interests and collect authentic data from an authentic environment to be further processed as an article. The mother tongue teacher helped to generate structured and *process-oriented* instructions for the article writing task. In the instruction, the emphasis was on the process of collaboratively gathering and elaborating the data and finally refining the articles. The role of the career counsellor was emphasized in the teacher-researcher meetings where the career counsellor was also a participant. It was decided that more time should be allocated for the students' web-based preparing phase within the career counselling lessons in order to help the students form some kind of image of the company even before the visit. The students prepared questions for the company's personnel, and these were sent to the company before the visit. This also enabled the company's personnel to respond to the students' particular interests (Table 6).

Table 6 Problematic aspects and decisions about changes in the first cycle

First cycle	Problematic aspects	Data source	Decision about change
2008	Teacher felt she had been left alone	Teacher's interview	More collaboration between the teacher and the researchers
	Missing link between visit and classroom studying	External experts' observations	Formulating structured inquiry tasks
			Preparing worksheets for the inquiry tasks
	Stereotypical view of industry professions before the visit	Students' interviews	Emphasis on the role of a career counsellor in preparing students to figure out about careers in S&T companies
	Unclear instructions for the reporting task	Teacher's reflections	Structuring the writing task, defining the aims and instruction

The second cycle was already a quite well-functioning entity. However, although the researcher team supported the teachers in all the phases, there were still some discrepancies in the inquiry work sheets. They guided the teacher to emphasize the correct answers and did not emphasize the inquiry process. They were modified to support the phases of the process, and new instructional pictures drawn by a graphic artist were added. The mother tongue teacher wrote explicit instructions for article writing and also guidelines for evaluating students' articles. These documents were included in the Teacher Guide.

In the final version, there are five different inquiry tasks in the procedure.

1. In the *dropping test*, students drop marble balls on sheets of different materials and examine the hit spot.
2. In the *electrical conductivity test*, students construct electric circuits and use objects made from different materials as components of the circuit and then examine conductivity with a light bulb.
3. In the *ripping test*, students rip sheets of different materials and examine the appearance of the traces made.
4. In the *heat conductivity test*, students stand sticks of different materials in a container containing hot water, then attach dried peas with butter to the sticks, and observe which of the peas drop off first.
5. In the *bending test*, students bend thin sticks made of different materials and see what happens, i.e., whether the sticks break or not and how they break.

After revisions made in the second cycle, the concrete design solutions, student book and teacher guide for the TLS *Materials around Us*, were finalized and published (Table 7).

8 Discussion and Conclusions

There were two levels of aims within this research project. The first of them was conducting a good-quality iterative DBR project and designing an inquiry-based TLS with features based on theories of motivation and interest and offering

Table 7 Problematic aspects and decisions about changes in the second cycle

Second cycle	Problematic aspects	Data source	Decision about change
2008	Unclear instructions in inquiry tasks	Video recordings of students' working	Re-constructing the instruction sheets, adding informative pictures
	Indefinite reporting instructions in the draft Teacher Guide	Researchers' reflections together with the mother tongue teacher	Explicit instructions for article writing task, revised with the mother tongue teacher
	Constructing a whole picture of the TLS	Researchers' reflections	Finalizing the Student Book and the Teacher Guide

justifications for the decisions made within the project. The second-level aim was to employ the designed TLS for enhancing students' motivation, interest, and engagement in their science studies. The research questions and discussion represent these two perspectives.

The process of designing and re-designing is discussed from the perspective of the evaluation criteria of DBR suggested by Juuti and Lavonen (2016, in this volume) and Edelson (2006). The focus of the iterative project was to design, in close collaboration with teachers, a materials science teaching-learning sequence (TLS) that employed authentic industry site contexts and IBST principles and encompassed theory-based features intended to enhance motivation and interest and enable interdisciplinary collaboration. The highly structured three-phase site visit model is a new innovation that enriches the traditional field visit practice and has a lot of potential to be used and applied by science teachers. This meets the requirements of novelty, relevance, and generalizability of the results of a DBR project. Also the project criteria of reflecting problematic aspects in authentic educational context and searching solutions in an iterative process were met. DBR seems to have been a suitable approach for developing the TLS, especially because of its cyclic nature. Such a multifaceted structure would have been impossible to construct in one go. Many essential aspects were revealed only when testing the TLS in an authentic school environment.

The pilot version of the TLS was based on the literature related to motivation and interest, but the guidelines for the teacher were too implicit. Alongside the iterative design project, various sets of data were collected during the process in order to meet the criterion of formative evaluation (Edelson 2006). Besides, the TLS was discussed reflectively in informal teacher-researcher meetings. As a result, the TLS got more structured and multi-faceted. Many aspects of the TLS were scrutinized and better practices were developed as shared activities with the teachers.

Based on the data, changes in the procedure are justified. Some changes were made after informal reflective discussions between teachers and researchers. The connection between the TLS and the curricular content aims was a serious concern of the external evaluators. Kisiel (2005) shares this concern when arguing that connecting schoolwork and visits helps teachers to see the benefits of a visit from the point of view of implementing the curriculum. As a result, the connection was tightened with structured inquiry task sheets. The experiments can be used flexibly in the context of materials science. Also the collaboration between the teacher and the company contact person was emphasized in the final version of the teacher guide in order to inform the company of the content-related aims of the students. Finally, the reporting task was re-structured, and the views of the mother tongue teacher were taken into account. It was revealed in the reflective discussions with the first cycle teacher that the reporting task was not engaging for all. Students' interest in inventing the questions for the visit was enhanced in the last cycle by telling them that the questions would be asked in an organized interview situation, in which there are many experts from different fields related to the company, and the students would use the answers for their later writing task. The students were given the possibility to choose who they wanted to interview. Probably, this autonomy supporting authentic situation, which was not directly controlled by the teacher, and the atmosphere in which the students were treated as grown-ups encouraged them invest in the task. This is in line with the IBST criteria suggested by Minner et al. (2010), as they argue that student responsibility is an essential feature of inquiry instruction. Autonomous regulation of behavior, in turn, is related to better quality learning outcomes (Deci and Ryan 2008). Linking the visit with the curriculum is in line with the arguments of Storksdieck (2001). He argues that the student preparation phase, examining the students' prior knowledge and attitudes, and a follow-up are essential to successfully connect the visit to the curriculum. The follow-up phase turned out to be a fruitful possibility for integrating school subjects representing different teaching cultures, in-detail science and mother tongue, in a way that the activities benefit the aims of both of these subjects. Drake and Burns (2004) define this kind of integration as interdisciplinary integration.

The TLS meets the criteria of IBST well (Minner et al. 2010). Students were responsible for scrutinizing the background information about the company over the web and autonomously planning and conducting the reporting task collaboratively. Students' active thinking was emphasized in the reporting phase. As this was done in collaboration with others, students constantly needed to challenge their own views and try to adopt their peers' perspectives as well in order to reach a compromise.

When considering the TLS from the point of view of the third research question, student motivation and interest, we relied on the students' interviews, because the ESIAQ did not reveal significant differences between students' evaluations of the TLS and ordinary science lessons. Almost all the values of M_1 and M_2 lie between 4 and 5 (scale 1–7), indicating that students rated both ordinary science teaching and the TLS rather positively, which is an encouraging aspect from the science education point of view but somewhat discouraging as the TLS is not significantly better. There are many possible reasons for this result. Firstly, it may be that the TLS did not affect students in any way. Laursen et al. (2007), who reviewed several papers about the effects of short-term interventions, argue that there is little convincing research literature about its statistically significant effectiveness (p. 50), no matter the popularity of the model. Secondly, students might also have had in their minds, despite our efforts, difficulties in differentiating between ordinary teaching and the module, as the module was intended to be closely connected with the curriculum. Thirdly, the operationalization of the concepts related to motivation and interest may have been unsuccessful and difficult for students to link with their image of themselves and their studies. The interviews offered more speculations about the difference between ordinary science lessons and the TLS.

Based on the interview data, the TLS appealed to the whole range of students despite their motivation orientation is a productive starting point for future designs of interdisciplinary teaching-learning sequences in out-of-school settings. All the students interviewed evaluated the TLS positively and would not rather have wanted to skip the site visit and study at school in a normal way. Especially remarkable was that the amotivated students' eyes were opened after seeing the relevance of their science studies as they connected school science and science applied in authentic settings. Also significant was the students' appreciation of the possibilities to choose their tasks. Lavigne et al. (2007) argue that science teachers' support of students' autonomy may have an impact on students' autonomous motivation towards science and even on their pursuit of working in a science-related domain, which is the long-term aim of such site visits.

The TLS brought together out-of-school learning and studying in the classroom in a manner that these two ways of studying science benefitted from each other. The students saw science applied in a real-life setting. According to Margel et al. (2008), meeting materials and their properties in different contexts and within different activities is also important from the learning of concepts viewpoint. The students prepared themselves in their school, met the materials science content in an authentic context, and then further deepened and processed it back in their school. We suggest that this is a reasonable way to use limited time resources so that students learn in a manner that also makes transfer possible. Moreover, despite the skills related to traditional school subjects, students also learn interdisciplinary skills introduced by Drake and Burns (2004), such as thinking and research skills.

9 Recommendations

The TLS can be implemented by following the student material and the teacher guide, but an in-service course is recommended to discuss the operating mechanisms of the basic psychological needs and their influence on student motivation. Motivating students should not be seen as isolated factor of the lesson but more like a philosophy centered round the activities.

In order to successfully accomplish the reporting task, students should be trained to use interviewing techniques and also the technological device for gathering data. Students may well use their own mobile device. Process writing technique should be practised. Collaboration with the mother tongue teacher is highly recommended in this phase. When examining the careers in the field of S&T, we recommend close collaboration between the science teacher and the career counsellor. It would be best if pairs or groups consisting of the science teacher, mother tongue teacher, and career counsellor would conduct the implementation in collaboration.

The inquiry activities connect the visit and the science content studied at school and offer a context for students familiarizing themselves with the properties of materials and the use of model-based reasoning. The organization of the inquiry tasks is explicated in the teacher guide.

Consequently, the teacher should be familiar with the essential features of the TLS in order to implement it effectively, as companies may have a strong, already existing idea about what a site visit should be like and what the students should be doing during these visits. Negotiating the best possible solution, which follows the guidelines of the TLS, is the teacher's responsibility.

Appendix 1: ESIAQ

EVALUATION OF SCIENCE INQUIRY ACTIVITIES STUDENT NUMBER: ______________________

DATE: ______________________ COUNTRY: ______________________

NAME: ____________________

For each of the following statements dealing with scientific inquiry activities, please indicate how true it is for you, using the following scale: **not at all true (1)** … **very true (7)**

	When I engage in a <u>science inquiry activity</u> …	not at all true			somewhat true			very true
1.	I enjoy the activity very much	1	2	3	4	5	6	7
2.	I think I am pretty good at the activity	1	2	3	4	5	6	7
3.	I put a lot of effort into the activity	1	2	3	4	5	6	7
4.	I do not feel nervous at all while doing the activity	1	2	3	4	5	6	7
5.	I believe I had some choice about doing the activity	1	2	3	4	5	6	7
6.	I believe the activity has some value for me	1	2	3	4	5	6	7
7.	I feel really distant from my peers while doing the activity	1	2	3	4	5	6	7
8.	The activity is fun to do	1	2	3	4	5	6	7
9.	I think I do the activity pretty well, compared to other students	1	2	3	4	5	6	7
10.	I don't try very hard to do well at the activity	1	2	3	4	5	6	7
11.	I feel very tense while doing the activity	1	2	3	4	5	6	7
12.	I feel like it was not my own choice to do the activity	1	2	3	4	5	6	7
13.	I think that doing the activity is useful for my science studies	1	2	3	4	5	6	7
14.	I really doubt that my peers and I would ever be friends through the activity	1	2	3	4	5	6	7
15.	The activity is boring	1	2	3	4	5	6	7
16.	After working at the activity for a while I feel pretty competent	1	2	3	4	5	6	7
17.	I try very hard to do the activity	1	2	3	4	5	6	7
18.	It is important to me to do well at the activity	1	2	3	4	5	6	7
19.	I am very relaxed while doing the activity	1	2	3	4	5	6	7
20.	I don't really have a choice about doing the activity	1	2	3	4	5	6	7
21.	I think the activity is important to do because it can help me in learning	1	2	3	4	5	6	7
22.	I feel I can really trust my peers participating in the activity	1	2	3	4	5	6	7
23.	The activity does not hold my attention at all	1	2	3	4	5	6	7
24.	I am satisfied with my performance for the activity	1	2	3	4	5	6	7
25.	I don't put much energy into the activity	1	2	3	4	5	6	7

(continued)

	When I engage in a <u>science inquiry activity</u> …	not at all true			somewhat true			very true
26.	I am anxious while working on the activity	1	2	3	4	5	6	7
27.	I feel that I have to do the activity	1	2	3	4	5	6	7
28.	I would be willing to do similar activities more because they have value for me	1	2	3	4	5	6	7
29.	I'd like to interact with my peers participating in the activity more often	1	2	3	4	5	6	7
30.	I would describe the activity as very interesting	1	2	3	4	5	6	7
31.	I am pretty skilled at the activity	1	2	3	4	5	6	7
32.	I feel pressured while doing the activity	1	2	3	4	5	6	7
33.	I do the activity because I have no other choice	1	2	3	4	5	6	7
34.	I think doing the activity could help me to learn science	1	2	3	4	5	6	7
35.	I feel close to my peers during the activity	1	2	3	4	5	6	7
36.	I think the activity is quite enjoyable	1	2	3	4	5	6	7
37.	I couldn't do the activity very well	1	2	3	4	5	6	7
38.	I do the activity because I want to do it	1	2	3	4	5	6	7
39.	I believe that doing the activity could be beneficial for me	1	2	3	4	5	6	7
40.	I don't feel like I could really trust my peers who are participating in the activity	1	2	3	4	5	6	7
41.	When I am doing the activity, I think about how much I am enjoying it	1	2	3	4	5	6	7
42.	I do the activity because I have to do	1	2	3	4	5	6	7
43.	I think the activity is an important activity	1	2	3	4	5	6	7

Appendix 2: AMQ

ACADEMIC MOTIVATION FOR LEARNING SCIENCE STUDENT NUMBER: ________________
DATE: ______________________ COUNTRY: ________________________
NAME: __________________________________

WHY DO I LEARN SCIENCE?
Using the scale below indicate to what extent each of the following items presently corresponds to one of the reasons why you learn science.

For each of the following statements dealing with scientific inquiry activities, please indicate how true it is for you, using the following scale: **not at all true (1)… very true (7)**

	Why do I learn science?	Does not correspond at all			Corresponds moderately			Corresponds exactly
1.	Because I have the impression that it is expected of me	1	2	3	4	5	6	7
2.	To show myself that I am a good student	1	2	3	4	5	6	7
3.	Because I choose to be the kind of person who will know many things as an adult	1	2	3	4	5	6	7
4.	Because it's important to me to learn science	1	2	3	4	5	6	7
5.	Because I enjoy the feeling of acquiring knowledge about science	1	2	3	4	5	6	7
6.	For the enjoyment I experience when I grasp a difficult subject in science	1	2	3	4	5	6	7
7.	Because it will help me make a better choice regarding my career orientation	1	2	3	4	5	6	7
8.	For the "high" feeling that I experience when I am having discussions with interesting science teachers	1	2	3	4	5	6	7
9.	Because studying science allows me to continue to learn about many things that interest me	1	2	3	4	5	6	7
10.	Because I think it is good for my personal development	1	2	3	4	5	6	7
11.	For the pleasure that I experience in knowing more about science	1	2	3	4	5	6	7
12.	Because I would feel ashamed if I couldn't discuss with my friends about things concerning science	1	2	3	4	5	6	7
13.	I don't know why I study science, and frankly, I don't give a damn	1	2	3	4	5	6	7
14.	In order to get a more prestigious job later on	1	2	3	4	5	6	7
15.	For the "high" feeling that I experience while reading about various interesting science subjects	1	2	3	4	5	6	7
16.	Because science learning allows me to experience a personal satisfaction in my quest for excellence in my studies	1	2	3	4	5	6	7
17.	Because I really like science learning	1	2	3	4	5	6	7

(continued)

	Why do I learn science?	Does not correspond at all			Corresponds moderately			Corresponds exactly
18.	Because I would feel guilty if I didn't study science	1	2	3	4	5	6	7
19.	Because I'll get in trouble if I don't do so	1	2	3	4	5	6	7
20.	For the pleasure I experience when surpassing myself in s cience studies	1	2	3	4	5	6	7
21.	Honestly, I don't know, I truly have the impression of wasting my time in studying science	1	2	3	4	5	6	7
22.	I once had good reasons for learning science; however, now I wonder whether I should continue	1	2	3	4	5	6	7
23.	Because I choose to be the kind of person who knows matters concerning science	1	2	3	4	5	6	7
24.	For the satisfaction I feel when I am in the process of accomplishing difficult exercises in science	1	2	3	4	5	6	7
25.	Because I want the teacher to think I'm a good student	1	2	3	4	5	6	7
26.	For the satisfied feeling I get in finding out new things	1	2	3	4	5	6	7
27.	Because for me, science learning is fun	1	2	3	4	5	6	7
28.	I don't know why I am studying science	1	2	3	4	5	6	7
29.	In order to have a better salary later on	1	2	3	4	5	6	7

Appendix 3: Interview Questions

Semi-Structured Interview, Questions

Guided questions or themes discussed with the students during the interview.

Part 1: Motivation

Orientation

Can you please tell me about the site visit and the learning tasks related to it?

1. *What was most interesting or motivating in the site visit TLS?*

What else was interesting or motivating?
Ask about the following features of the site visit if the student does not mention anything about them.

2. *What kinds of possibilities to influence the way things were done during the site visit TLS did you have?*

   Was it interesting or motivating to have an influence on the way things were done during the site visit TLS?
   Did you have possibilities to plan the learning activities?
   Did you have an influence on the way the learning tasks were done?
   Did you have an influence on choosing the learning tasks?
   Did you have an influence on the order the learning tasks were done?
   What else were you allowed to decide about?
   Was it nice to influence the way things were done during the site visit TLS?

3. *What kinds of possibilities to work together with your classmates did you have during the site visit TLS?*

   Did working together with your classmates increase your motivation or interest towards studying?
   Did you feel close to your group members?
   Was it nice to work together with the other pupils?
   Did you have a possibility to plan the learning activities with the other pupils?

4. *Did you feel competent during the learning tasks related to the site visit?*

   Are you sure you were competent?
   Did feeling competent increase your interest or motivation towards studying?
   What made you feel yourself competent? (Was it your own, your teacher's or other pupils' view?)
   Did you feel competent during the ICT tasks related to the site visit TLS?
   Did you feel your competency was appreciated?
   Could you do well some other thing related to the site visit TLS?

5. *Can you please tell me about your feeling of interest and enjoyment during the site visit TLS.*

   Did you feel convenient during the learning tasks related to the site visit?
   Did your feeling of interest and enjoyment have an influence on your interest and motivation towards the site visit TLS?
   What learning tasks affected your interest most during the site visit TLS?

6. *Can you please tell me about the motivating or interesting content or context of the TLS.*
7. *Overall, what do you think about the TLS?*

Part 2: Learning

8. *What do you know about products of the site visit company?*

   Do you know, what materials the products is made of?
   Do you know, how are products manufactured from materials? What is the manufacturing process of a product like?
   Do you know, what properties the products have?
   Do you know, where are the products are used?

9. *What do you know about the materials used in the company?*

   Do you know, what raw materials are used to produce materials the company uses and where these materials come from?
   Do you know, how the materials are manufactured from raw materials?
   Do you know, what properties these materials have?
   Do you know, how the properties of the materials are analysed?
   Do you know, a simple structural mode that explains a property of the material, describes the structure of each material?

10. *What do you know about the occupations in the site visit company?*

    Do you know, what kind of occupations there are in the site visit company?
    Do you know, what kind of education is required for each job?
    Do you know, what the people who do the various jobs have to do at work?
    Do you know, what kinds of skills/abilities/knowledge/attitudes/ways of thinking are required in each occupation?

11. *What do you think about site visit as a way of working?*

    What do you think about the advance preparation of the site visit?
    What do you think about the site visit?
    What do you think about studying after the site visit?
    What do you think about the site you visited?
    How do you assess your own working?
    What do you think you have learned during the site visit?

12. *Tell us something about the mindmaps you constructed before and after the site visit.*

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The Iterative Design of a Teaching-Learning Sequence on Optical Properties of Materials to Integrate Science and Technology

Italo Testa and Gabriella Monroy

1 Introduction

> Let me check if I understood well… Is this module a way to teach some geometrical optics by means of the optical fibres, isn't? (*Experienced physics teacher*)
>
> Well, this project aims at favouring students' interest on basic physics notions through some aspects of modern physics as materials science… (*Researcher in physics education*)

The above dialogue took place in a cold afternoon meeting at the very beginning of the collaborative partnership of university researchers and school teachers who developed the teaching-learning sequence (TLS) described in this chapter. The above comments well exemplify some of the difficulties that historically affected the development of science and technology integrated approaches (Aikenhead 1994a).

For instance, Cajas (2001) reports that the "bridge project," an activity in which students are offered the opportunity to simulate the design and testing of a bridge, may be a useful context to learn science and technology contents (gravity, forces and tensions, properties of materials) and to apply design principles (how to cope with constraints, analysis of trade-offs). However, implementations of such an activity revealed that students focused more on producing an artefact ("the bridge") rather than reflecting on design details and concepts needed to improve such an artefact.

In a similar vein, Roth (2001) finds that technology-driven lessons focused on designed artefacts would hardly help students use some sort of scientific discourse to justify the adopted design, thus impeding them to deal with and deepen the knowledge of the involved science concepts.

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On another hand, Benenson (2001) argues that technology education may be useful to understand the relationships between science and technology in terms of how science knowledge impacts on technological innovations and how these in turn influence new science discoveries. An example is the "City Technology Curriculum" in which the students are involved in activities concerned with how to create maps of a city, how to design circuits and control devices, packaging issues and graphic coding useful for street signs. The author claims that such a curriculum may be useful for a variety of disciplines (mathematics, language arts, and social studies) and specially for science since it is possible to exploit a "real" design problem to start data collection in experiments in which the goals are related to the solution of the proposed problem. While such an approach may usefully put on close tracks design and inquiry tasks, science and technology contents may remain substantially separated and simply "juxtaposed" (Aikenhead 1994b).

Silk et al. (2009) reported the results of the implementation of a technological design-based unit on electronics and simple electrical circuits in an urban setting and compared such results with control groups who followed an inquiry and a textbook-driven curriculum. Results show significant gains of all involved groups, with a greater effect size for the treatment group. Very similar results are reported by Schnittka and Bell (2010), Fortus et al. (2004), and Puntambekar and Kolodner (2005). However, all these studies seem to support technological design merely as a methodology for learning usual science contents, thus disregarding the issue of a more profound integration between science and technology (Geraedts et al. 2006).

The proposal by Schnittka and Bell (2010), aimed at addressing heat transfer and energy, resembles the approach developed 20 years earlier by Jones and Kirk (1990) for teaching electrical capacitance. While in Schnittka and Bell's proposal, the context is provided by a series of design-and-test tasks about the construction of dwelling insulating boxes for penguins, in Jones and Kirk's approach, a techno-object or a technological outcome is the starting point to address science concepts related to the functioning of the objects.

To a certain extent, all these approaches basically use an already constructed (or the design of an) object as a more or less appealing way to address science contents (Fensham 1988; Gilbert 1992), leaving the constructed prototype or the object somewhat aside once that scientific concepts are addressed. Their main strengths are the possibility to show the relevance of technology in everyday life and to study science facts and laws at the basis of a techno-object. However, the main weakness of these approaches is to not treat in an integrated way the science and technology contents.

In the theoretical chapter, building on views on nature of science and technology (Arthur 2009; Ziman 1978), we proposed a rationale through which a driving *theme* is "reconstructed," with the aim of identifying a "common core." The reconstruction process is inspired by the education reconstruction (Kattmann et al. 1998) framework. More specifically, the identified theme is first deconstructed into a scientific content-related *component* and a technology-related *component*. Then the components are both "elementarized.". For the scientific component, this means to enucleate the key ideas at its basis. Examples of key ideas for a scientific content as electric circuits could be "electrostatic force," "density of charge," "energy," etc. For the technology component to elementarize means to identify first the technological process or device to which it refers and then the natural phenomenon that it harnesses. For instance, reading of bars codes is based on laser technology, which harnesses stimulated emission as natural phenomenon. In the final step, the enucleated key ideas and natural phenomena are integrated in what is called the common core. The TLS is then constructed on the basis of this common core.

In this chapter, we will describe what happened in the next three years from the comment in that afternoon meeting until the finalized TLS, focusing on its design, development, evaluation, and redesign.

2 The Iterative Process for the Development of the TLS

According to Meheut and Psillos (2004):

> A TLS is both an interventional research activity and a product, like a traditional curriculum unit package, which includes well-researched teaching–learning activities empirically adapted to student reasoning. Sometimes teaching guidelines covering expected student reactions are also included (p. 516).

In general, as a research-informed product, the design of any TLS should take into account many issues related to, e.g., students' and teachers' conceptions about the chosen content, theories of learning, and external (e.g., school curricula) factors. Moreover, the development of research-based activities requires many pedagogical choices on behalf of designers, e.g., which experiments to carry on, which questions to guide the activities, and so on.

In the particular case of the design of a TLS, which aims to integrate science and technology following the rationale described in the theoretical chapter, it should necessarily be taken into account the quality of the elementarization process and how it is actually implemented in the proposed activities. It follows that design of such a TLS cannot be a linear but rather an iterative process.

Previous studies in a curriculum design showed the effectiveness of iterative processes to develop TLSs. For the sake of brevity, we discuss the proposal by Andersson and Bach (2005), being an exemplar to clarify what iteration process means. The overall developmental strategy is constituted by a "design phase," followed by a "trial phase" whose results inform, by means of a feedback mechanism, the "redesign phase." The key tenet is that the improvement of learning can be achieved by a strict collaboration between researchers and teachers at the level of both phases. Such collaboration should aim at disseminating the research results as well as at harmonizing the different viewpoints of researchers and teachers.

A very simplified model of such an iterative development process is reported in Fig. 1.

Basically, the design phase includes all the actions undertaken by the designers to develop the TLS. The outcome is a set of goals and a draft of the TLS. The authors suggest that the format of such TLS should be a kind of teacher's guide, which also includes some useful "background information" as, e.g., the nature of

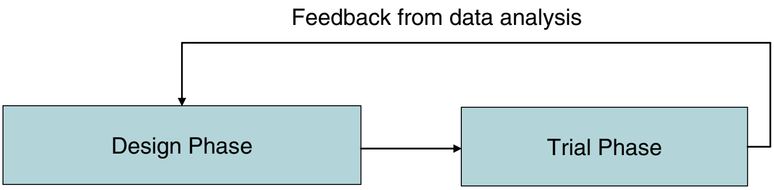


Fig. 1 Simplified model of the TLS development

the content addressed, its educational relevance, and the research results about students' difficulties about this content. Then the TLS is implemented in a school context, and the main results are used to feed a redesign phase.

While the design and trial phases have been given a significant role in science education research (see Meheut and Psillos 2004, for a review), there are few examples that address the following general issues related to the use of feedback data on the redesign phase: what important features should be looked at in implementing a TLS in order to improve its design? How should the data obtained be used to improve the TLS? What outcomes should be investigated in the implementations of the TLS so to facilitate amendments of emerged problematic aspects?

A first example concerns the development process of the PLON project (Eijkelhof and Lijnse 1988). Developers of this curriculum report that hints for its redesign came from a variety of sources: teachers' and students' views about materials, contents, and unit structure; an evaluation to assess students' motivation, improvements in cognitive skills and learning outcomes about science contents; an analysis of content organization and chosen contexts through discussions with experts, newspaper reading, and student interviews.

A second example concerns the development of the STS-based textbook *Logical Reasoning in Science and Technology* (Aikenhead 1994c). A first version was implemented in a classroom, and feedback from students and teachers helped to develop an optimized version. This was then used by volunteer teachers with no previous training; evidence from class observations led to further improvement of the textbook.

Both examples show that in the iterative process, numerous design aspects have to be compared with empirical evidences from school practice; consequently, developers' initial choices may change substantially after implementation in standard classes. Designers, for instance, may consider it worth taking into account what students dislike or may neglect aspects that motivate/interest the students. Local or national cultural features may play an important role.[1]

In the specific case of science and technology integration, the way to describe how results from the trial phase may actually affect optimized versions of the TLS in the design phase is still to be fully documented. This case study aims at contributing to science education in addressing this issue.

[1] The PLON Traffic unit (initially disliked by many students, later one of the most popular) is a remarkable example.

3 Research Question

The research questions that guided this study were as follows:

- RQ1. What were the changes made during the iterative development process of the TLS?
- RQ2. What data have suggested the main changes?
- RQ3 How do these changes relate to the "Science and Technology common core" of the TLS?

The questions address the issue of *documenting* how the results of the trial phase(s) may affect the subsequent design phase(s) of a TLS. We chose to focus on the changes, derived directly from the data analysis, that were made to each of the subsequent versions of the TLS. The above issue is addressed using as "case" a TLS which aims at integrating science and technology in an innovative way. We expect, therefore, that the "common core" of the TLS will play a central role, especially to better specify the "feedback from data analysis" block of Fig. 1 schematic model.

4 The Common Science and Technology Core

In this section, we describe, in the first place, the process that informed the identification of a suitable common science and technology core in order to answer the above research question.

The starting point was the choice of the content, namely, the optical properties of materials area. The reason for such a choice was mainly due to the fact that in this content area, the links between technological/social demands and science progress are easily recognizable. In particular, past centuries and recent years show clearly that, on the one hand, some technological optical tools have been indispensable for unforeseen scientific progress (e.g., the telescope for astronomy, the microscope for cellular biology, the optics spectroscopy); on the other hand, very impressive technological objects (e.g., video cellular phones, CD/DVD players, cameras, spectacles/binocular/telescope), which many students are familiar with, exploit at their core basic optics phenomena.

Taking into account that the TLS was intended for 15- to 16-year-old students, with basic concepts of geometry and elementary algebra as pre-requisites, the educational reconstruction (see below) took advantage from the analysis of literature in science education about the content-related to optical properties of materials, i.e., the main alternative conceptions held by students about basic concepts of optics. These are briefly described in Sect. 4.1, while in Sect. 4.2, the process of identification of the common science and technology core is described.

4.1 Students' Difficulties with Geometrical Optics

Many studies have been devoted at investigating students' ideas about vision and geometrical optics.

First of all, it has been shown that primary students hold the Pythagorean view that vision is an active process, the origin being the subject himself (Guesné et al. 1978; Jung 1981). This result, plausibly related to the phrasing of common language ("killing sight," "piercing eyes," "X-ray vision"), has been confirmed by other researchers with older students (Andersson and Karrqvist 1982; La Rosa et al. 1984; Palacios et al. 1989). In another view, the light first hits the eye, which either reflects or emits a kind of a beam which finally reaches the "seen" object (Crookes and Goldby 1984; Ramadas and Driver 1989; Bendall et al. 1993). In other cases, there may be no direct connection between eye and object, provided it is luminous (Osborne et al. 1993).

Secondly, students think that light is a "material medium" (Palacios et al. 1989; Watts 1985) or a "resident medium" (La Rosa et al 1984) which fills the space "like a sea" (Selley 1996) and does not propagate, remaining nearby the source (Stead and Osborne 1980). Only for a minority of students think that light propagates along a rectilinear path (Andersson and Karrqvist 1982; Guesné 1984).

Some studies (Ambrose et al. 1999; Langley et al. 1997; Selley 1996) indicate difficulties with image's constructions via the "rays diagram" (drawing of an image using few emblematic rays). To this concern, the ray model itself can be misleading and confusing, since many students think of rays as real entities (Viennot and Chauvet 1997; Viennot et al. 2005).

Thirdly, some students think that mirrors reflect all the incoming light and that the image is resident on the mirror or just behind it (Galili et al. 1991; Goldberg and McDermott 1986). Another naïve conception is that the object's image *travels* to the mirror or a lens in the presence of light (Bendall et al. 1993; Galili et al. 1993). It has also been found that some students think that the image always remains focused independently of the distance between lens and screen, that half a lens produces half an image (Galili and Hazan 2000; Goldberg and McDermott 1987), and that a lens can also increase the velocity and energy of light passing through it (Palacios et al. 1989).

Finally, studies have shown that some students fail to recognize reflection and refraction as due to the interaction of light with matter and/or materials and think they are two mutually exclusive phenomena: when there is reflection, no refraction can take place, and vice versa (Palacios et al. 1989). In the same study, confusion between refraction and diffraction is also reported; another study (Singh and Butler 1990) has shown that students have difficulties in drawing refracted rays in not standard situations (e.g., rays hitting plane and curved interfaces as the face of an equilateral prism or a semi-circular glass block) and in recognizing conditions necessary for total internal reflection (e.g., most students do not consider total internal reflection, unless the angle of incidence is very large).

4.2 Identification of the Common Core

The optical fiber has been the chosen driving theme for the TLS development in the content area of optical properties of materials. According to our aim for integrating science and technology, first scientific and technological components of the optical fibers theme have been identified, then reconstructed and elementerized.

We decided that the study of light behavior in an optical fiber (scientific component) could be reconstructed using as key scientific ideas how the light travels and can be guided within the fiber. To this concern, it followed that the index of refraction of the material and total internal reflection had to be addressed.

The technological component (e.g., data communication by means of the travelling light in the optical fiber), at its very core, relies on the phenomenon that light bounces, via total internal reflections, at the interface between two materials that must have specific indices of refraction (the inner material must have a greater index of refraction).

Thus, the above reconstruction process leads us to identify the "common core" for the two components – scientific and technological – of the chosen driving theme as *total internal reflection and index of refraction*.

Starting from this common core, the activity sequence has been developed in a way that the scientific and technological components could not be disentangled; this implies that the proposed TLS addresses in a very intelligible way the relationships between science and technology in the case of optical fiber. For instance, very early in the teaching sequence, the activities focused on the study of the behavior of light at the interface between the two materials of an optical fiber, called core and cladding, which allows students to understand how and under which conditions light can be guided along a specific path and how optical fibers do so. Both refraction and reflection phenomena have been interpreted as specific cases of deviation of light from the rectilinear path; the quantitative description has been given in terms of ray model, of the refractive index and critical angle. In particular, the role played by the refraction index of the fiber's material(s) was clarified via concrete examples; moreover, the analysis of different types of fibers has been introduced to facilitate the awareness about why so diverse fibers are used in many diverse fields.

This common core is substantiated, therefore, in the following general aims of the TLS:

- To improve student' learning about the concepts of the common core (e.g., index of refraction, total internal reflection as the principle at the basis of light guidance)
- To improve students' ideas about science and technology relationships

We will give some details about the activity sequence in the following section.

5 Construction of Instruction of the TLS

To achieve the overall aims of the TLS, we designed experimental, modeling, and design activities. We give here some details about each group of activities.

5.1 Experimental Activities

A guided inquiry approach was adopted in the experimental activities of our TLS. Students in small groups investigate an experimental situation presented by the teacher who encourages them to express their ideas and formulate hypotheses by means of structured worksheets. Moreover, the teacher is required to suggest the scientific question to be addressed, to help perform the experiment (when needed), and to foster students to test their own hypotheses and reflect on the initial scientific question/problem. The students, on the other hand, are required to make measurements inasmuch as possible on their own, to analyze the data to answer the initial problem, and to support their conclusions with sound arguments based on the observed evidence.

As emblematic example of experimental activity featured in the TLS, Fig. 2 shows a typical outcome of the so-called *water-jet* experiment. It clearly shows both the light path at the interface between two different materials (water and air) and the light guidance within the water. The water jet has been used as the prototype of an optical fiber.

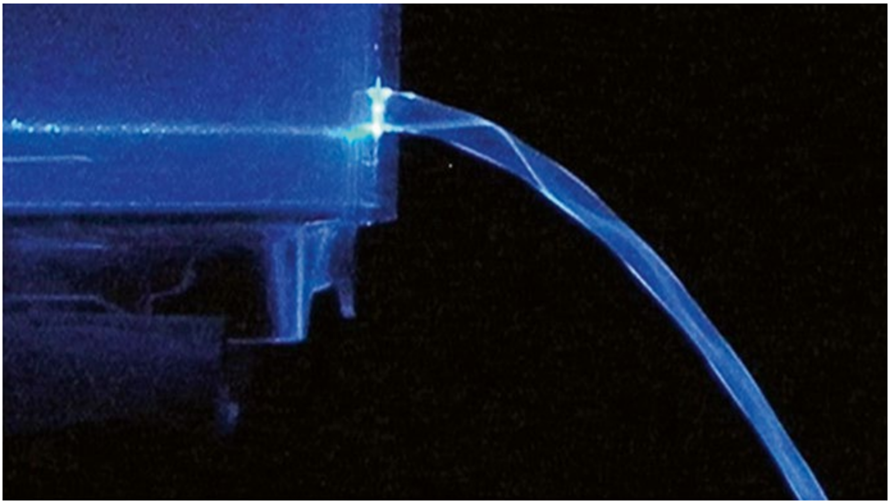


Fig. 2 The water-jet experiment. A laser beam is sent into a water tank with a small hole producing a tiny water jet. In the water jet, the laser beam undergoes total internal reflection on the water-air interface

In this activity, the students in small groups are asked to provide a possible explanation for the observed light path. The main aim is to provide evidence of the necessity of having at least two materials in order to guide the light along a specific path.

The *water tank* is a second emblematic experiment in which both refraction and total internal reflection are clearly visible (Fig. 3). To facilitate readers, we report a schema of the water tank experiment in Fig. 9.

In this activity, the students in small groups, each with a similar tank, qualitatively investigate about the dependence of the laser path inside the tank and the entrance angle value. The main aim is to introduce to students the reflection and refraction phenomena and to give a first idea that reflection is the natural phenomenon at the basis of light guidance.

5.2 Modeling Activities

A descriptive modeling approach (Lijnse 1998) inspired by "from Real to Ideal" rationale (Sassi 2001) was used in the TLS. In general, the "Real to Ideal" rationale starts from experiments which explore real, complex facts and proceeds to the identification of phenomenological regularities which are transformed in rules, through more "clean" experiments, in which secondary effects have been minimized. It proceeds further to modeling these rules with simple mathematical functions. The final step is the abstraction towards the ideal case/model representing the appropriate physics law. This rationale is implemented in the module through a method proposed by our group (Testa and Lombardi 2007, Monroy et al. 2008) by means of which it is possible to carry out accurate measurements and build-up effective descriptive models of phenomena where a trajectory is visible and an image is produced via a digital camera. The trajectory can be that of an accelerated electron beam, as it is the case in the Thomson-like apparatus, or of a water wave in a ripple tank or of a laser beam propagating in different media. The basic idea is to model

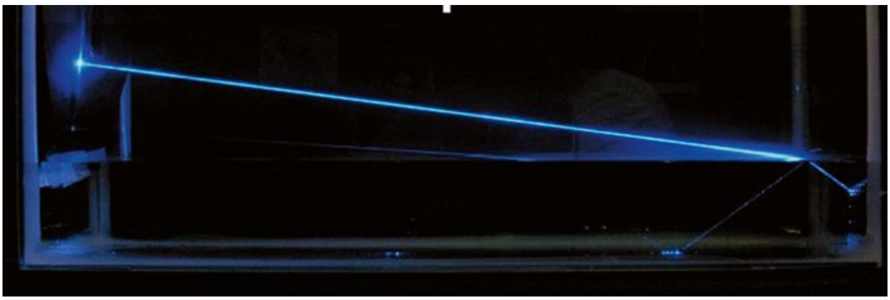


Fig. 3 The water tank experiment. A laser beam enters from bottom right. By changing beam direction, refraction and total internal reflection at the water-air interface are observable. Visibility of light beam in air is enhanced by means of some smoke

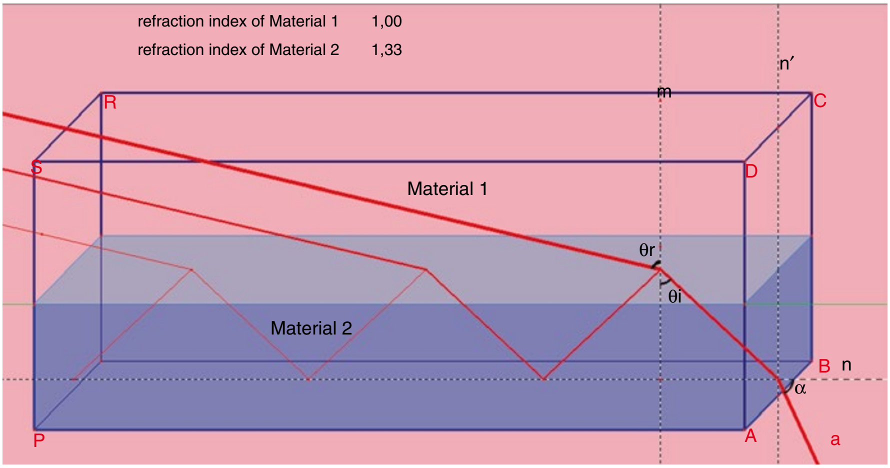


Fig. 4 Schematic representation of the water tank experiment. The ray enters from bottom right. If n_1 is the refractive index of Material 1 and n_2 is the refractive index of Material 2, with $n_2 > n_1$, it can be proved that entrance angle θ, incident angle θ_I, and refracted angle θ_r satisfy the following relationships: $n_1 \sin(\alpha) = \sqrt{n_2^2 - n_1^2 \sin^2(\theta_r)}$; $n_1 \sin(\alpha) = n_2 \cos(\theta_i)$

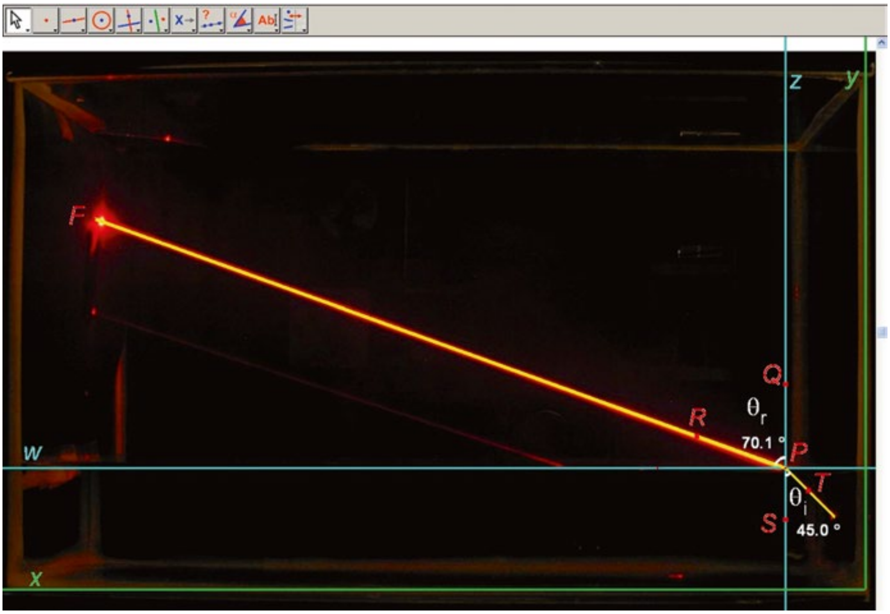


Fig. 5 Modeling of the refraction of a light beam in the water tank experiment. From the incident (45.5°) and refraction (70.1°) angles measurements, it is possible to measure the refraction index of the water relative to air ($n \cong 1.33$)

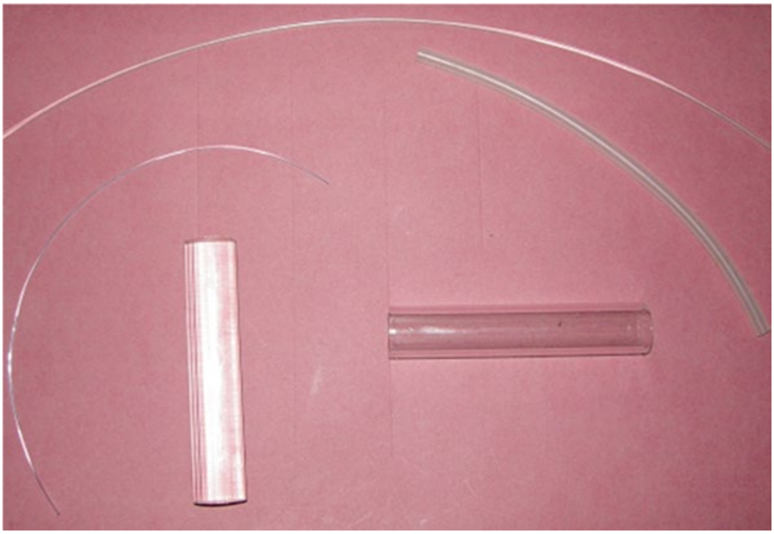


Fig. 6 Objects used to test students' predictions for the design of a light guide

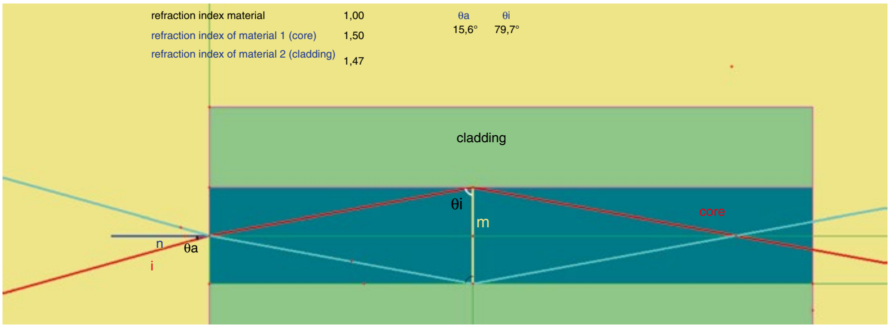


Fig. 7 Simulation in Cabrì environment of the design of an optical fiber. The simulation allows to change the refraction index of the materials of the virtual optical fiber in order to see how these changes affect its design

the trajectory by means of geometrical entities (line, circumference, parabola, etc.) and then to measure its parameters by means of the well-known educational software Cabrì Géomètre.

In the TLS, the quantitative relationships that describe light behavior in the water tank experiment are obtained by the students. In particular, each group of students imports digital pictures of the experiment in the Cabrì environment and models the observable light path with segments, lines, and angles. Hence, it is possible to perform angles measurements and derive, for instance, reflection and refraction laws (Fig. 10). Then the students are asked to look back at the original experiment and interpret it on the basis of these laws.

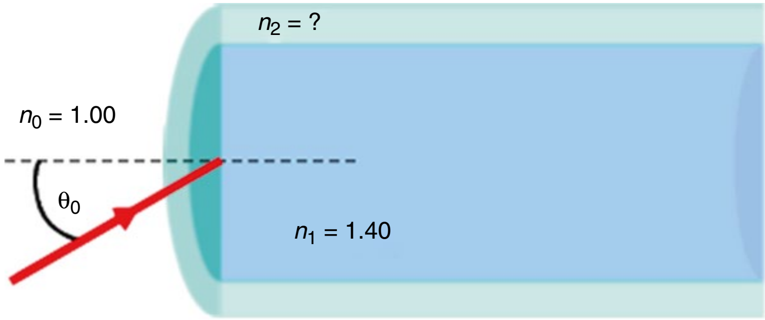


Fig. 8 Image from the students' questionnaire used in the first and second studies

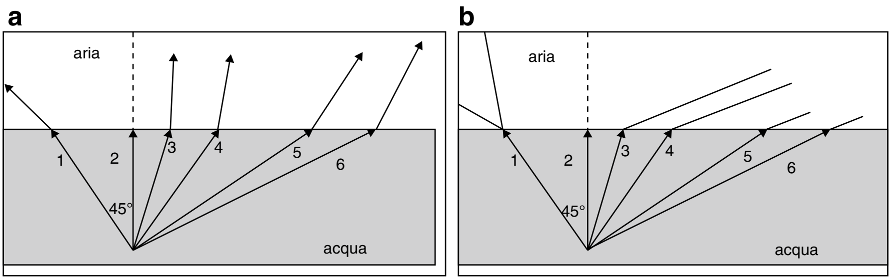


Fig. 9 Student's drawing of light beams refracted from water to air (T1). In (**a**), all refracted beams are incorrect. In (**b**), only beams 3 and 4 are correct

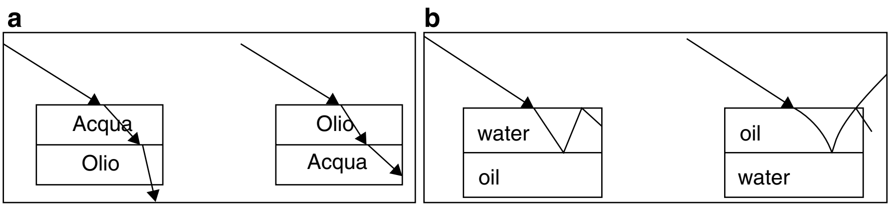


Fig. 10 Correct (**a**) and incorrect (**b**) student's drawing of light beams refracted from air to water to oil and from air to oil to water (T2). After 10, the next number is 12

5.3 Design Activities

In our TLS, the experimental and modeling activities are accompanied by design activities. These activities are inspired by those presented in previous studies, in particular, those described in Benenson (2001). The main difference is that the students are not required to produce an artefact or a prototype as a result of the design tasks. Rather, the students are driven to find out the design principles at the basis of

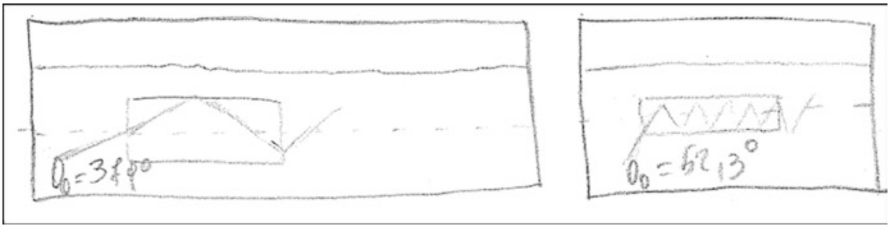


Fig. 11 Partially correct student's drawing of light path in a plastic tube ($n = 1.57$) immerged in water ($n = 1.33$). The answer is correct when light enters in the tube at an angle of 37.9° (*left drawing*) since the incidence angle on plastic-water interface (58.7°) is greater than the critical angle (57.9°). The answer is not correct when the entrance angle is 52.3° (*right drawing*): in this case, the incidence angle is 47.9° which is smaller than the critical angle. Note that θ_0 is the angle between the beam and the dotted line

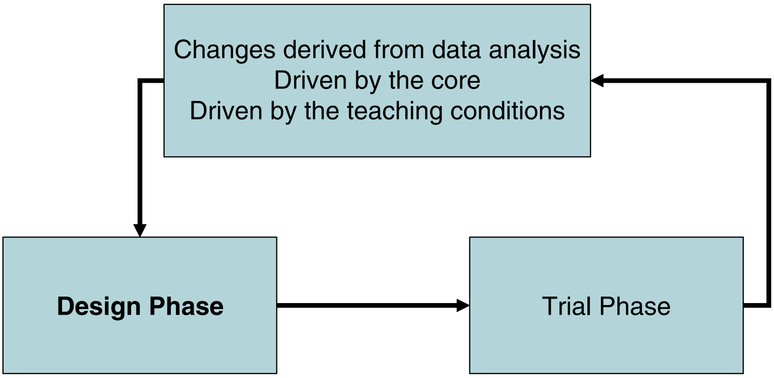


Fig. 12 Improved model of the development of a science and technology integrated TLS

the technological objects addressed (light guides and optical fibers). The design activities are carried out as written tasks and simulations in the Cabrì environment. In the first design activity, which takes place at the very beginning of the TLS, the students are asked to identify the characteristics of a light guide starting from the observation of behavior of different objects as fishing lines, rubber tubes, hollow and filled plastic rods (Fig. 11). Then, in a second activity, after the experimental and modeling activities about the water jet and the water tank experiments, the students are asked to choose suitable materials for the design of the core and cladding of an optical fiber using a simulation in Cabrì environment. Particular focus is on the appropriate indices of refraction that allow light to follow a specific path into the fiber (Fig. 12). Once the appropriate indices are identified, the students compare the obtained values with those reported by a look-up table of materials.

6 Implementation of the Iterative Development Process

The partnership that developed the TLS was composed of four university researchers, four school teachers, and two teacher-researchers. In agreement also with Andersson and Bach's rationale (2005), the university researchers and the two teacher-researchers actually designed the TLS in the form of students' worksheets (SWs) and teachers' notes (TNs). The SWs did not follow a rigid structure, but the following main aspects were always featured: questions to inform group reflection and discussion about scientific and technological aspects; clues for the conclusions to be drawn at the end of the activities. To facilitate the reader, two examples of SWs are reported in Appendix A. The TNs aimed at giving guidance to the teachers for performing the proposed activities as well as for clarifying and elaborating the main ideas addressed. Also for the TN, a rigid structure was avoided; the common features were indications for performing the suggested experiments and guidance for the proposed computer activities.

The four teachers (two experienced, two novice) either made a content analysis of the subsequent versions of the SWs or implemented the TLS (see below, Tools and Sample section).

The collaboration was substantiated in about 15 meetings held at the university. The first three were dedicated at illustrating to the teachers some research results relevant for the design of the TLS (the educational reconstruction model, inquiry- and context-based teaching, nature of science and technology, and relationships between science and technology). The following two meetings were devoted at discussing a "preliminary" version of the TLS with the aim of improving the activity sequence and harmonizing the viewpoints of researchers and teachers before the first implementation in a pilot to test the overall feasibility and coherence. The subsequent five meetings were devoted to analyze the data from the pilot study, obtaining a feedback which drove the design of a "first" version of the TLS. This version was then implemented in a first round of experimentation in two standard school contexts. The final five meetings were devoted to iterate the process resulting in a new feedback and a "second" version of the TLS implemented in another round of experimentation in two new standard school contexts.

The timeline of the collaborative partnership with the corresponding stages of the development process is shown in Table 1.

7 Preliminary Activity Sequence

The preliminary version of the TLS was constituted by a set of activities clustered in three separate units accompanied, as said above, by SWs and TNs. Unit 1 was basically devoted to light guides and the principle underlying light guidance (total internal reflection). Unit 2 was mainly devoted to optical fibers and related design issues (core, cladding, acceptance angle, etc..). Table 2 summarizes the proposed

Table 1 Synopsis of iterative process, partnership timeline, and TLS development stages

Iterative process stage	Partnership meetings	TLS development stage
Design phase	Three for dissemination of research results	Preliminary version
	Two for discussion about TLS	
Trial phase (pilot study)		
Design phase (after first feedback)	Five for discussion of results of implementation and changes to be made	First version
Trial phase (first study)		
Design phase (after second feedback)	Five for discussion of results of implementation and changes to be made	Second version
Trial phase (second study)		

Table 2 Preliminary version of the TLS about optical properties of materials

Time	Activities (code)	Intended objectives
Unit 1		
2 h	 Qualitative experiments with light sources and common objects (E1)	To familiarize with vision, the role of the eye and of the medium
1 h	 Qualitative experiments with optical fibers, optical fibers lamps, rubber tubes, fishing lines (E2)	To gather first clues about the basic properties of optical fibers

(continued)

Table 2 (continued)

Time	Activities (code)	Intended objectives
1 h	 Experiment: “water jet” (E3)	To be aware of the basic principles for guiding the light To familiarize with rectilinear and non rectilinear propagation of light. To qualitatively describe reflection phenomena
1 h	 Experiment: ‘water tank’ (E4)	To freely explore reflection and refraction phenomena
2 h	 Quantitative experiment on refraction (E5)	To measure the index of refraction of water with respect to air To describe reflection and refraction phenomena in terms of the “ray” model of light

(continued)

Table 2 (continued)

Time	Activities (code)	Intended objectives
1 h	 Cabrì measurements on images of a laser beam refracted from water to air (S1)	To be aware of the difference between the phenomenon and its (abstract) representations To model light propagation phenomena with a ray model
1 h	 Simulation of refraction of light propagating from air to water and from air to a liquid (water, olive and sunflower oil, vinegard) (S2)	To infer quantitative relationships between incident and refracted rays To state the refraction law and define the refraction index To become aware that the refraction index is a material's property

(continued)

Table 2 (continued)

Time	Activities (code)	Intended objectives
1 h	 Cabrì measurements on images of laser beam reflected in the water (S3)	To state the reflection law To determine the relationships between the incident, reflected and refracted angles
1 h	 Simulation of refraction and Total Reflection phenomena of light propagating from water to air (S4)	To calculate the value of the critical angle

(continued)

Table 2 (continued)

Time	Activities (code)	Intended objectives
Unit 2		
1 h	 Qualitative experiments and observations with water tanks, laser beams optical fibers, rubber tubes, fishing lines (E6)	To become aware that in order to have a light guide one must provide a transparent material surrounded by another transparent one of smaller refraction index
0.5 h	 Qualitative experiments on different possible optical fibers (E7)	To become aware of the role of the fiber's cladding surrounding the core
		To collect evidences on how an optical fiber mush be designed
0.5 h	 Comparison between the 'water jet' and the behavior of an optical fibre (E8)	To become aware that the cladding's refraction index influences the "acceptance angle"

(continued)

Table 2 (continued)

Time	Activities (code)	Intended objectives
1 h	 Qualitative experiment with a glass fibre in air and in water (E9)	To determine qualitative relations between the value of the acceptance angle and the difference n_1–n_2
1 h	 Cabrì simulation of the propagation of a ray in a step-index optical fiber with one signal propagating in it (S5)	To familiarize with the “step index” optical fiber structure (core, cladding) To define the angular aperture (and numerical aperture) of a step index optical fiber To determine the relation between the value of the acceptance angle and the difference n_1–n_2 To understand that when n_1–n_2 is small light undergoes less internal reflections at the interface core-cladding To define the relationship between numerical aperture and core and cladding refraction indices
1 h	 Qualitative observations and experiments with different water tanks and a laser beam (E10)	To be aware of the problem of attenuation in a fiber To understand why optical fibers are very transparent and how this is accomplished (e.g., by doping the material)

(continued)

Table 2 (continued)

Time	Activities (code)	Intended objectives
1 h	 Qualitative observations on images of experiment of total internal reflections in water (E11)	To identify factors that influence attenuation: amount and dimension of the diffusing (bulk) particles, length of the light path To understand qualitatively the basic mechanisms that impair the possibility to transfer light (power) at 100 % efficiency: diffusion, absorption, and scattering

activities and the learning objectives of Unit 1[2] and 2.[3] The symbol  indicates an experimental activity, the symbol , a computer activity. For the sake of clarity, the indication of whether the activity was an experimental, a modeling, or a design activity is omitted. The reader is invited to refer to previous sections to find the correspondence.

As it can be seen from the table, one of the main features of the TLS was the blend of experimental and simulation activities. The rationale of this choice was related to the fact that the synergy of laboratory work and simulation activities is powerful from an educational viewpoint since the competences that can be gained through both of them are diverse and complementary. Moreover, such interaction can be useful to address the following issues: perception, on behalf of the teachers, that the laboratory activities have more disadvantages than advantages from the educational viewpoint since unforeseen events may impair to reach the intended learning objectives; distinction between simulation and model, which often are considered as synonymous. From the operative viewpoint, throughout the TLS activities, students first gather "clues" about light guidance and optical fibers through experimental situations and formulate hypotheses for the mechanisms at the basis of the observed behaviors. Plausibility of the hypotheses provided by the students is then tested in the simulations. Moreover, since materials used for constructing optical fibers appropriate to telecommunications are expensive and not always easy to find, the simula-

[2]The university researchers proposed to begin the TLS with an activity about vision, to test students' naïve ideas about the vision mechanism and refer to research results.

[3]Unit 3 was intended as an extension of the TLS and thus to be implemented only in suitable school contexts (for instance, 17- to 18-year-old students).

Table 3 Samples and teachers involved in the three trials

Pilot study	First study	Second study
Duration		
16 h in four sessions, over about 3 weeks	12 h in four sessions, over about 3 weeks	10 h in five sessions, over a period of about 1 month
Samples: secondary school students (15–16 years old)		
Nine from a scientific lyceum	18 from a scientific lyceum	25 from a scientific lyceum
	17 from a technical school	18 from a technical school
Teachers involved		
Experienced teacher (T0)	Experienced teacher (T1)	Novice teacher (T3)
	Novice teacher (T2)	Novice teacher (T4)
Data collected		
Students' and teacher interviews	Assessment tasks, teachers' interviews	

tion of the optical fiber can guide students to understand how changes in the material structure (i.e., change in refraction index) can modify traveling light patterns.

However, due to this blend of experimental and simulation activities, for the partnership, this *preliminary version* had apparently a quite different structure with respect to the habitual Italian syllabus modules (see Appendix B). For this reason, as said above, it was agreed to try this version in a special context for a pilot study (see below). The next sections will deal with how the TLS evolved from this preliminary version to a first and a second version.

8 Tools and Samples

As reported in Table 1, the development process exploited three rounds of trials *(pilot, first and second study)*, with five different teachers and different students' samples involved (Table 3). Four teachers (T0–T3) were part of the partnership; T4 was involved at a later stage only in the implementation of the TLS.

The main aim of the *pilot study* was that of testing the overall feasibility of the TLS. Hence, the data collected came from a semi-structured post-instruction students' and teacher's interview. The students' interview featured some qualitative questions about the concepts of the common core, i.e., index of refraction, total internal reflection, and light propagation in an optical fiber. The teacher interview featured five questions about the activities (see Appendix C). A grounded theory approach (Strauss and Corbin 1990) was used to analyze teachers' answers. Content analysis of the SWs was also carried out by the partnership after the implementation of the pilot study to find out possible flaws and errors.[4]

[4] We did not analyze the answers given by the students to the SWs. Content analysis concerned only the wording of the SWs.

Table 4 Rubrics adopted to analyze students' responses to the question "what are the relationships between science (S) and technology (T)?

Category	Description
Level 2 (L 2)	S and T interact reciprocally
Level 1 (L 1)	S precedes T, T precedes S, S and T are independent
Level 0 (L 0)	No clear distinction or similarity identified

During the *first and second study*, the data collected were teachers' interview (same as that used in the pilot study), students' answers to a pre- and post-questionnaire (see Appendix D), and a new post-instruction interview (see Appendix E). The students' questionnaire featured three items, each with five *true/false* questions (maximum score = 1 for each item) focused on the concepts of the common TLS core. One open question about science and technology relationships was also inserted in the questionnaire. The latter question was introduced to investigate if the focus on the common core was effective also in improving students' ideas about science and technology at the epistemological level, which was a main aim of the TLS. The students' answers to this question were analyzed with a rubric inspired by the categories proposed by Gardner (1999) (Table 4) since they represented increasing degrees of understanding of the science and technology relationships. To inspect about possible differences between the pre- and post-test questionnaire, the non-parametric Wilcoxon Signed Ranks test was used.

The new version of the interview featured three open quantitative tasks where students had to draw correct light paths in different situations.

As it will be discussed below, duration of the instructional time was shorter in the first and second studies with respect to the pilot study since the first and second versions did not feature the preliminary activity on vision and one experiment on refraction. The slight difference in teaching time between the first and second studies was due to an extra activity about graded index optical fibers carried out in the first study which will not be discussed here.

9 Results

The findings of the TLS implementations (pilot and first/second study) are presented according to the changes introduced in the TLS from the outcomes of the analysis of the collected data. Evidences and reasons for the changes are also given. For the pilot study only, content analysis of SWs is also reported.

9.1 Pilot Study

The preliminary version of the TLS reported in Table 2 was used in this study, and only post-instruction interviews both for teachers and students have been analyzed. The changes related to students' learning outcomes are reported in Table 5.

Table 5 Synopsis of changes made to the preliminary version of the TLS in relation to students' learning outcomes after the pilot study

Exemplar evidence	Researchers' reflections	Changes
Q. So you think that there is a relationship between the intensity of the light beam and the index of refraction?	It is plausible that observation of the remarkable different visibilities of a laser beam in, e.g., water and air, due to smoke in air, has lead the students to overlook the deviation of the direction of propagation of the beam when crossing the interface of two media, focusing only on the possible factors that affected light visibility.	Change conventional presentation order of the geometrical optics contents by addressing first refraction and then reflection in order to focus from the start on beam deviation; and to better relate the results of the water jet (E3) and water tank experiments (E4)
"S. I think so… because when the light beam is not refracted but completely reflected it does not loose any intensity… instead when there is refraction the light beam looses its intensity "		Specify more in detail what are the hypotheses at the basis of the "ray" model in geometrical optics (activities E4 and S1)
		Highlight the role of the refraction index of a material on light behavior in it (activity S5)

Table 6 Synopsis of changes made to the preliminary version of the TLS in relation to data collected during the pilot study

Exemplar evidence	Researchers' reflections	Changes
Q. So what do you think of the activities?	It has to be taken into account that it can be difficult for teachers to introduce inquiry activities if they are not familiar with them. Such difficulty may lead to spending more time than necessary on hands-on activities with inaccurate results.	Eliminate the experiment E5 and postpone the measurement of the index of refraction of water in the activity with Cabrì S1.
"T0. I think that this should be the way to teach physics… the laboratory… they like it very much… but it is too much time consuming… we addressed two physics laws in more than twelve hours… for me it would be impossible during a regular teaching… and that experiment on the index of refraction… it doesn't work… I think we lose time with it."		Emphasize in the teachers' notes the general teaching-learning principles underlying the design of the module and the suggestions useful to correctly implement the proposed experimental activities

(continued)

Table 6 (continued)

Exemplar evidence	Researchers' reflections	Changes
Q. What do you think of the optical fiber as context?	This excerpt indicates that science teachers may not be able to address how some technologies are related to scientific contents addressed in the curriculum. As a consequence, the optical fibers may be only addressed as a "new" way to introduce geometrical optics and then left aside.	Highlight the role of optical fibers as driving theme to motivate students by introducing a scenario focused on the use of fibers especially in telecommunication (films and mp3 downloads, fiber cables connections, etc.). Recall them throughout the module
"T0. [W]ell the module is innovative… you can teach geometrical optics laws with fibres… however I had difficulties in understanding how they are used in informatics and telecommunication… when it comes to E-mule as one student said… well I was lost."		Highlight in activities E3, E4, S4 that optical fibers technology harness a phenomenon that can be described through mathematical relationships between measurable parameters

From the students' interviews, as far as the *common core* of the TLS is concerned, this preliminary version seemed to be not so effective in helping students understand the role of the index of refraction. For instance, to the question if the refraction index of a substance depended on the quantity of substance, only one out of nine students answered "[n]o, since it is a property of the substance," while four students related the refraction index to the laser beam "intensity." On the other hand, the activities seemed effective in helping students achieve a correct understanding of the total reflection mechanism at the basis of the fibers' functioning. Actually, almost all students, when asked to explain why the phenomenon of total reflection is responsible for light to travel along curved paths, answered correctly that otherwise "there could be refraction of the light beam and the light could loose [*sic*] its intensity."

The changes introduced on the basis of the teachers' answers to the post-instruction interview are reported in Table 6 with exemplar excerpts and the corresponding researchers' considerations.

Finally, the content analysis of the SWs allowed also to recognize that, overall, the proposed sequencing of science contents was rather traditional (reflection, refractive index, refraction, etc.), with only little emphasis on light path and guidance and correspondingly too much on vision. Hence, it was decided to eliminate the first activity (E1) on vision in order to dedicate more time to light path and guidance. Secondly, the Cabrì activities seemed only complementary and introduced too late in the sequence. To help students acquire a deeper knowledge of this tool essential for the TLS, the basics of Cabrì have been suggested as prerequisite.

The new version of the TLS took about five meetings to be finalized, including the redesign of the assessment tasks, before being implemented in the first study.

Table 7 Results of pre- and post-instruction questionnaire in the first study (true/false questions)

	Normalized average number of correct answers		
Sample	Pre	Post	Z*
1 (N=11)[a]	0.09	0.70	−2.943*
2 (N=13)[a]	0.08	0.73	−3.187*
Z^*	−0.326[ns]	−1.019[ns]	–

[a]These were the students present at both pre- and post-instruction questionnaire;
*Significant, $p<0.003$.

9.2 First Study

We report first the results of the students' learning outcomes (questionnaire and interview to some[5] selected students). As far as the 15 true/false questions of the first three items of questionnaire, a comparison of students' average number of correct answers (normalized to number of questions) shows a significant gain between pre- and post-test for both students' samples (Table 7). Differences between the samples in the pre- and post-test are not significant. Hence, this first version seemed effective in improving involved students' knowledge about the science and technology concepts of the common core. More specifically, the results of the pre-test were poor and, in a way, expectable for questions about total reflection, index of refraction, and their use in the optical fibers, since the students had initially a scarce knowledge about these contents.[6]

In the post-test, students in sample 1 showed more difficulties than students in sample 2 about total reflection (67 % of correct answer vs. 82 % on average). On the other hand, both samples showed some difficulty in quantitative reasoning about the path of a light beam in an optical fiber (respectively 60 % and 58 % of correct answers on average). For instance, when asked if in the situation of Fig. 8 one has to know the cladding refraction index in order to draw the path of a laser beam in the core of the optical fiber, almost all the students answered, incorrectly, "yes."

Some difficulties emerged in the post-instruction interviews to the students. For instance, when explicitly asked to draw refracted rays when light goes from the water to the air (Task 1), the eight students gave either a wrong (Fig. 9a) or a partial response (Fig. 9b). Therefore, the conditions for total internal reflection had not been well understood.

Similar difficulties (six wrong, incomplete, or partial responses) emerged when students were asked to draw refracted rays when light goes from air to water to oil and from air to oil to water (Task 2, Figs. 10a and b).

[5]Four students of each sample were selected: two with the highest score (0.90) and two with the lowest score (0.55) in the post-instruction questionnaire.

[6]Although basic geometrical optics laws are addressed, at least in a qualitative way, at middle school level (11–13 years old) in Italian Science curriculum.

Some difficulties have been also found in students' answers to Task 3 in which they were asked to justify the light path in a plastic tube immerged in water for two different values of the entrance angle. All the students failed to recognize the condition for total internal reflection at the plastic-water interface (Fig. 11). It is evident that these students did not take into account in their drawing the importance of the refractive index of the cladding of fiber.

When the students showed the above difficulties, some of them were prompted to change the situation using air instead of water as surrounding medium and a hollow tube. In this case, they succeeded in the task. For instance, when asked:

> Q. ok, let's study a simpler situation… for example, air instead of water and an hollow tube … Can we use such hollow tube to guide the light?

two students answered:

> we can not use it since air has the lowest refraction index and it is difficult to find a cladding with refraction index lower then the air and avoid refraction of the propagating beam.

and two more students answered that:

> if I bend the hollow tube the light undergoes refraction.

It is then plausible to infer that this first version of the TLS was still not completely effective in helping students understand in a quantitative way the behavior of light in the optical fiber.

Overall, from the above results, the partnership introduced the following specific changes: extend the activities aimed at understanding the role of the cladding in the fiber (E7 and E8); include in the TLS two sessions (*briefings*) of 1 h each in which some summarizing tasks were collaboratively solved by the students and the teacher.

The results of the analysis of students' responses to the open question about the relationships between science and technology are reported in Table 8.

Students with an informed view about science and technology relationships (L2) increased between the pre- and post-test in both samples, and differences were significant (Wilcoxon Signed Ranks Test, sample 1: $Z=-2.236$, $p=0.025$; sample 2: $Z=-2.000$, $p=0.046$). For instance, one student of sample 1 claimed in the pre-test:

> Technology is an artificial representation of nature. (L0)

In the post-test, the same student wrote:

> there is a strong link… technology is based on some scientific phenomena and on results of scientific inquiry…[O]n the other hand an accurate work in Science is based on the high progresses of Technology. (L2)

Another student, sample 2, wrote in the pre-test:

> Science discovers the things of the Earth, Technology makes experiments on an object.

while in the post-test, he wrote that:

> the more advanced Technology… the more Science can deeply study natural phenomena on which Technology is based.

Table 8 Results of pre- and post-instruction questionnaire (open question) in the first study

	Pre-test	Post-test
	Sample 1 ($N=11$)	
L 2	2	4
L 1	5	6
L 0	4	1
	Sample 2 ($N=13$)	
L 2	4	6
L 1	7	7
L 0	2	0

Finally, in the post-instruction interviews, both involved teachers valued positively some features of the TLS. Teachers' views suggested further changes to this version, resumed in Table 9.

As a result of the envisaged changes, the second version of the TLS is reported in Table 10. The intended objectives according to what emerged from the data and the main differences with the preliminary version of the TLS are also reported.

9.3 Second Study

The results of the pre- and post-instruction questionnaires show significant differences in students' responses in both involved samples (Table 11).

Students showed poor results in the pre-test. As far as the *common core* contents, in the post-test, for sample 3 students, the frequency of correct answers in the questions about index of refraction and total internal reflection (respectively 0.76 and 0.80) has been satisfactory. A quite similar result emerged in questions about propagation of light and total reflection in optical fibers (respectively, 0.67 and 0.71). The students' outcomes to the question about total reflection are very similar (0.73 and 0.75, respectively).

As far as the post-instruction interviews, eight students (four for each sample) were chosen, with the same criteria used in the first study. In task 1, three students were able to correctly draw refracted rays from water to air; in task 2, two students answered drawing correctly the refracted ray from water to oil and from oil to water; in task 3, only one student, of sample 4, was able to correctly draw the propagation of light rays in the optical fiber immersed in water.

In the open question about science and technology relationships, the students showed some gain between the pre- and post-test (Table 12). More specifically, Wilcoxon Signed Ranks Test is significant for sample 3 ($Z=-3.464$, $p=0.001$) but not for sample 4 ($Z=1.732$; $p=0.083$). To this latest concern, it is worth noting that the teacher of sample 4 had addressed previously in this class some aspects about nature of science and technology.

For instance, one student of sample 3 claimed in the pre-test:

> Science is the inquiry… technology applies the studies of Science

Table 9 Synopsis of changes made to the first version of the TLS in relation to data collected during the first study

Exemplar evidence	Researchers' reflections	Changes
Q. So what do you think of the activities? "T2: Well I think there are several activities… many teachers would not implement the TLS simply because it is too long."	Many activities designed to clarify some aspects of optical fibers were repetitive and could lead to loss of interest on behalf of the students.	Eliminate some qualitative experiments (E6-E10-E11)
Q. What do you think of the worksheets? "T2: [S]ometimes it is hard for the students to follow the activities and write down… This is quite new for them."	The worksheets in some cases may distract the students from performing experiments and simulations.	Limit the request of answering to the tasks of the SWs only to those cases in which the teacher may have no experience with guided inquiry approaches. Had the teacher some previous experience with such approaches, students are guided to perform the activities by the teachers without the use of worksheet. Class discussions are managed directly by the teachers.
Q: What do you think of the optical fiber as context? "T1: Well, I think it is a very good starting point." Q: Did you find any difficulties in addressing it? "T1: [W]ell, in some cases there were too many activities in between, for instance, the use of optical fibres in informatics and the principle of functioning of the fibres."	The time gap between the presentation of the scenario and the activity with the fiber and with the subsequent water-jet experiment (E3) leads to some superfluous repetitions.	Unify in the same session the scenario and experiment E2, in order to relate more strictly the techno-object with the scientific concepts underlying its behavior. As a consequence, E2 activity was shortened to half an hour.
Q. What do you think about the way in which geometrical optics is addressed in the TLS? "T2: [W]ell I think it is a good way to address reflection and refraction… and I liked very much the fact that we have addressed refraction and then reflection."	It seems that the main focus is on the order of presentation: refraction before reflection.	The presentation of reflection and refraction as two linked aspects of the deviation of light, which occur at the same time, has been emphasized in experiment E4.

(continued)

Table 9 (continued)

Exemplar evidence	Researchers' reflections	Changes
Q. Did the students find any difficulties on the mathematics addressed? "T1: [W]ell, I think we had to spend some more time on angles, sinus, cosines… things like that… I also think that students lose more or less the compass with all that mathematics."	During the activities, before the formalization of the refraction law, some time had to be devoted to addressing trigonometry concepts.	The basic concepts of trigonometry were considered as prerequisites, to be addressed before the implementation of the TLS, in order to spare teaching time.
Q. What do you think about the possibility to address aspects of science and technology? "T1: [W]ell… I think that it is possible to show that optical fibres are an interesting application of geometrical optics… that makes the activities different from usual ones… for instance, a pupil said to me to have enjoyed the hands-on activities because he saw something real but that he disliked the Cabrì activities… I think that some of them did not understand at all the meaning of these activities."	It seems that the TLS did not embed completely the principles of science and technology integration as envisaged in our theoretical framework, in particular, the optical fiber is seen as an application of science concepts. Moreover, design of the optical fiber is not emphasized.	Highlight the *common core* of science and technology for the optical properties of materials introducing in the activities' sequence how to determine the numerical aperture of a fiber using only geometrical reasoning and the refractive indices of core and cladding. This was done extending from 1 to 2 h the tasks concerning optical fibers design (E9 and S5) based on using Cabrì simulation. In this way, it was also possible to clarify the role of the Cabrì activities.

while in the post-test, he claimed:

> Science and Technology are strictly linked… thanks to technology the work of scientists is facilitated… since it is possible to better reproduce natural phenomena in laboratory.

Similarly, one student of sample 4 in the pre-test wrote that:

> Technology depends on the growth and development of science

while in the post-test, he claimed:

> Technology and Science are linked one to the other because thanks to Science and its studies we can discover new phenomena and hence use them for new technologies which in turn allow deeper scientific studies.

Generally, the post-instruction interviews to the teachers revealed a positive attitude towards the TLS. For instance, the teacher of sample 4 (T4) explicitly acknowl-

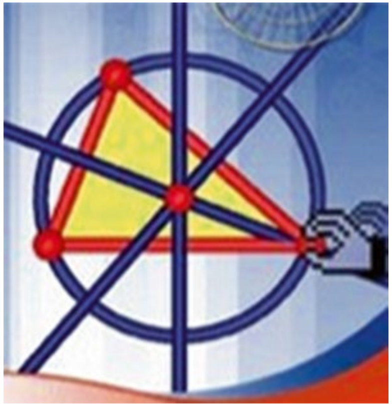
Table 10 Overview of the second version of the TLS

Time	Activities code	Intended objectives	Differences w.r.t. the preliminary version
Unit 1			
1 h	 Scenario + qualitative experiments with optical fibers, optical fibers lamps, rubber tubes, fishing lines (E2)	To gather first clues about the basic properties of optical fibers (same)	Introduction of the scenario and elimination of the activity about light sources (E1). More focus on epistemological aspects of the common core
		To show why, how, and by means of what materials light can be guided along curved paths (new)	
		To be aware of the science and technology relationships (new)	

(continued)

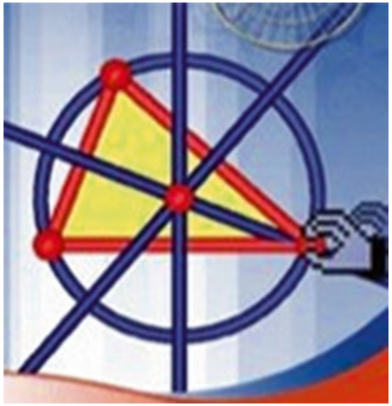
Table 10 (continued)

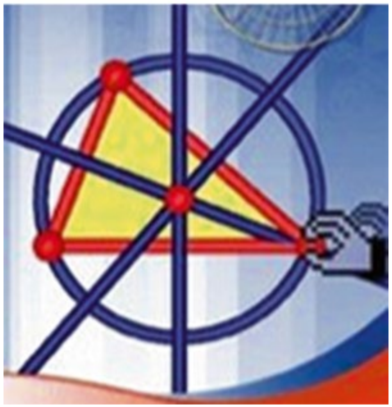
Time	Activities code	Intended objectives	Differences w.r.t. the preliminary version
1 h	 Experiment: "water jet" (E3)	To be aware of the basic principles for guiding the light (same)	More focus on the relationship between light guidance and the presence of an interface between two materials
		To familiarize with rectilinear and non rectilinear propagation of light (same)	
		To qualitatively describe reflection phenomena (same)	
		To be aware of the role of the interface between two homogeneous materials (new)	
1 h	 Experiment: "water tank" (E4)	To freely explore reflection and refraction phenomena (same)	More focus on why light deviates at the interface between water and air and on why the visibility of the beam is different in water and air
		To distinguish simple different ways for deviating the light (new)	
		To identify qualitative characteristics of light propagating in materials (new)	

2 h	 Cabrì measurements on images of a laser beam refracted from water to air (S1) + simulation of refraction of light propagating from air to water and from air to a liquid (water, olive and sunflower oil, vinegar) (S2)	To measure the index of refraction of water with respect to air (formerly addressed in E5)	Elimination of the quantitative experiment on refraction (E5) due to the excessive uncertainties in the estimation of the values
		To describe reflection and refraction phenomena in terms of the "ray" model of light (formerly addressed in E5)	Focus on reflection and refraction as phenomena of interaction between light and materials
		To be aware of the difference between the phenomenon and its (abstract) representations (same)	
		To infer quantitative relationships between incident and refracted rays (same)	
		To state the refraction law and define the refraction index (same)	
		To become aware that the refraction index is a material's property (same)	
		To understand that refraction and reflection always occur at the interface (new)	

(continued)

Table 10 (continued)

Time	Activities code	Intended objectives	Differences w.r.t. the preliminary version
2 h	 Cabrì measurements on images of laser beam reflected in the water (S3) + simulation of refraction and total reflection phenomena of light propagating from water to air (S4)	To state the reflection law (same)	
		To determine the relationships between the incident, reflected, and refracted angles (same)	
		To calculate the value of the critical angle (same)	

1 h	 +  Briefing of previous activities	To strengthen concepts introduced so far (new)	More focus on relating all the activities carried out about light guides,
			More emphasis on how to resolve tasks about light guides

(continued)

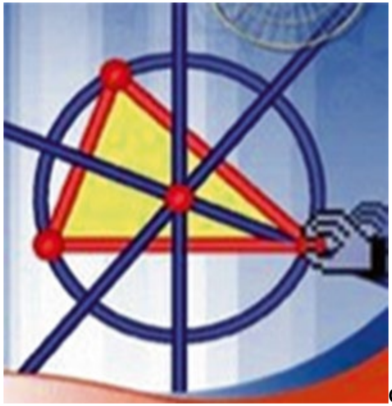
Table 10 (continued)

Time	Activities code	Intended objectives	Differences w.r.t. the preliminary version
Unit 2			
1 h	 Qualitative experiments on different possible optical fibers (E7) + comparison between the "water jet" and the behavior of an optical fiber (E8)	To become aware of the role of the fiber's cladding surrounding the core (same)	Elimination of Activity E6, condensed in the "briefing of previous activities" (see above)
		To collect evidences on how an optical fiber must be designed (same)	More emphasis on how other properties of materials may influence light path
		To become aware that the cladding's refraction index influences the "acceptance angle" (same)	Strengthen the connection between experiments in E7 and E8
		To identify correct light paths in a fiber (new)	
		To understand the role of transparency of a fiber's materials (new)	

4 h	 Qualitative experiment with a glass fiber in air and in water (E9) +	To determine qualitative relations between the value of the acceptance angle and the difference $n_1 – n_2$ (same)	Elimination of E10 and E11

(continued)

Table 10 (continued)

Time	Activities code	Intended objectives	Differences w.r.t. the preliminary version
	 Cabrì simulation of the propagation of a ray in a step-index optical fiber with one signal propagating in it (S5)	To familiarize with the "step index" optical fiber structure (core, cladding) (same)	Strengthen the relationships between real experiment and simulations
		To define the angular aperture (and numerical aperture) of a step index optical fiber (same)	Extension of the activities
		To determine the relation between the value of the acceptance angle and the difference $n_1–n_2$ (same)	
		To understand that when $n_1–n_2$ is small light undergoes less internal reflections at the interface core-cladding (same)	
		To define the relationship between numerical aperture and core and cladding refraction indices (same)	
		To become aware of how the design of optical fibers depends on the properties of its materials (new)	

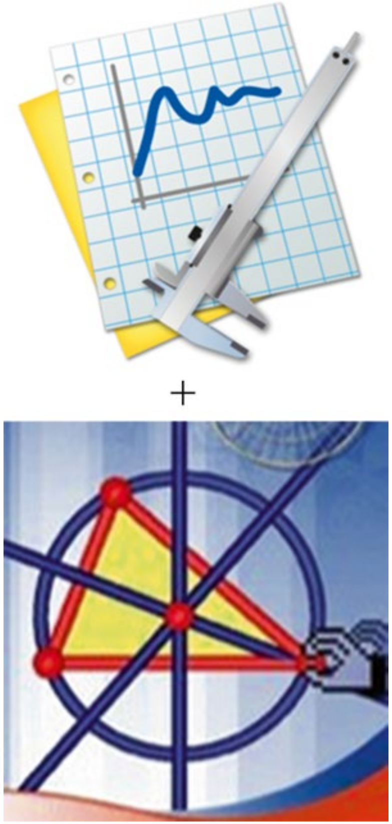
1 h	 Briefing of previous activities	To strengthen concepts introduced so far (new)	More focus on relating all the activities carried out about optical fibers More emphasis on how to resolve tasks about optical fibers

Table 11 Results of pre- and post-instruction questionnaire in the second study (true/false questions)

	Normalized average number of correct answers		
Sample	Pre-test	Post-test	Z
3 ($N=17$)[a]	0.08	0.74	−3.634*
4 ($N=15$) [a]	0.06	0.70	−3.440*
Z	−0.626[ns]	−1.052[ns]	

[a]These were the students present at both pre- and post-instruction questionnaire
*Significant, $p<0.001$

Table 12 Results of pre- and post-instruction questionnaire (open question) in the second study

	Pre-test	Post-test
	Sample 3 ($N=17$)	
L 2	2	6
L 1	7	11
L 0	8	0
	Sample 4 ($N=15$)	
L 2	5	6
L 1	7	8
L 0	3	1

edged the importance of the integrated core of science and technology contents and the possibility to "do some physics" at the meantime:

> Q. So what do you think of the optical fibers as context? And what about the activities?
>
> T4: [I]t was fundamental… we did not separate the Science from the Technology… the scientists from the engineers… students learnt that total internal reflection is at the basis of optical fibers… it is not usual in a Technical school to address the physics principle at the basis of a technology… it is fundamental… and very new!… I had to address optical fibres but I did not know how to do it… you know… there are no experiments to carry out… it is difficult to obtain a real fibre… and it is difficult to use it… instead with this TLS the students could see some experiments and make some measurements… and the duration was right… I did also some physics… That's important.

Interestingly, concerning the possibility of teaching physics contents with the proposed activities, the teacher of sample 3 (T3) received some critics on behalf of some of the students and some her colleagues:

> [O]ne (student) said that we always talked about optical fibers and that it was more motivating than usual physics classes… but another student said that this was not physics since there was not all the theory stuff… very illuminating for me… The same holds for some of the colleagues … the Science colleague asked me why was I always in the laboratory and not in the class… she said that the students in the laboratory did not concentrate on the concepts… also this is paradox, if you think about it!…
>
> [S]ome of them (students) did not… expect… these kind of activities… you know… we let them be scientists at least for a while… I think this is important for them… but other colleagues, specially those of Science and Mathematics do not let students be scientists… you know, all the scientific method stuff… hypotheses… testing, drawing conclusion… supporting or rejecting hypotheses… they think students do not know nothing at all… so how can they be scientists or understand what scientists do?

10 Discussion of Results

To answer the research questions of the paper, it is necessary to look back "a posteriori" at the whole feedback process (see Results section, particularly Tables 5, 6, and 9). We can group the changes introduced to the TLS in the following categories (RQ1):

- Aspects emphasized or highlighted – these changes concern modifications in the way to present the concepts during the activities.
- New activities introduced – these changes concern the inclusion of new teaching activities.
- Activities suppressed – these changes concern the elimination of teaching activities.
- Activities modified – these changes concern modifications in the length and sequence of the activities.

The data from which these changes were mainly drawn have been (RQ2) as follows:

- The students' answers to the pre- and post-questionnaires and post-instruction interviews
- The teachers' post-instruction interviews

The changes suggested by the students' data were mainly aimed at improving the understanding of the concepts of the common core. Therefore, we will define these changes as "driven by the core." The changes suggested by the teachers' data had the main goal to optimize the teaching time or to help in correctly implementing the proposed experimental and simulation activities. Therefore, these changes were not "driven by the core" of the TLS but rather by other factors and contextual/local circumstances pointed out by the teachers who implemented the TLS. We will define these changes as "driven by teaching conditions." Such definition implies, as a corollary, that the common core is *independent* of the teaching conditions. Table 13 resumes the main changes introduced according to the above categorizations (RQ3).

Drawing on the above results, we propose a more detailed description of the basic schema of Fig. 6, inferred from the case here described as a TLS aimed at integrating science and technology (Fig. 12). However, the schema can be easily generalized to TLS about a different content, had the designers provided a "core" which should be independent of the teaching conditions. With this schema, it is possible to specify how the feedback from the trial phase(s) affects the subsequent design phase(s).

In our case, the common core related to the integration of science and technology played a key role in the whole iterative development process. Without a clear identification of such a common core, it would have been difficult to account for the changes introduced in the various TLS versions in the science and technology integration perspective.

Table 13 Categories of the main changes introduced in the TLS

Driven by the core	Driven by teaching conditions
Aspects emphasized or highlighted	
Optical fibers, as any other technological object, harness a phenomenon that can be described through mathematical relationships between measurable parameters (activities E3, E4, S4), beam deviation first in refraction and then in reflection phenomena (activity E4)	
Relation of the results of the water jet (activity E3) and water tank experiments (activity E4), reflection and refraction as two linked aspects of the deviation of light, which occur at the same time (activity E4)	
Hypotheses at the basis of the "ray" model in geometrical optics (activities E4 and S1)	
Role of the refraction index of a material on light behavior in it (activity S5)	
New activities introduced	
Optical fibers scenario	Two sessions (briefings) of 1 h each to summarize previous activities' results
Activities suppressed	
Activity about vision E1	Experiment E5
	Qualitative experiments in E6-E10-E11
Activities modified	
Extended:	Reduced/unified:
Activities E7 and E8 aimed at understanding the role of the cladding in the fiber	Activity S1 and postpone the measurement of the index of refraction of water
Activities E9 and S5 (each from 1 to 2 h), i.e., the tasks concerning optical fibers design based on Cabrì simulation to determine the numerical aperture of a fiber using only geometrical reasoning and the refractive indices of core and cladding	Scenario and experiment E2 (shortened to half an hour) unified in the same session

With the improved model of Fig. 12, it is possible to describe in detail the development of any TLS and document if and how the results of the implementations actually impacted on their redesign. In particular, once those changes related to the core of the TLS are identified, it is possible to identify in an easier way the supporting conditions and hindering constraints not strictly connected to the core which are to be addressed in the design phase(s). Taking again our case as an example, we can infer that supporting conditions related to the teachers were, for instance, the habit of using experiments and inquiry approaches in usual practice, knowledge about epistemological aspects related to science and technology, awareness of students' learning difficulties about the specific topic addressed (geometrical optics), familiarity with the technological content (optical fibers). In a similar way, we can infer that some of the hindering factors which we addressed in the redesign phase were, for instance, teaching time constraints, students' pre-requisites, students' difficulties in answering the worksheets' questions.

11 Limitations and Conclusions

Let us first discuss some limitations of this study. Firstly, although our conclusions are supported by different sources of data (students' questionnaires, teachers' interviews, content analysis of the worksheets), we are conscious that the small number of students involved in each trial phase and the lack of control groups or random samples may represent a limitation to the possibility of generalizing the obtained result. The different teachers' attitudes may have also influenced the results, e.g., the focus on specific concepts addressed in the TLS, or the time devoted to the activities has been a teachers' choice. For all these reasons, we are aware that a direct comparison of the results of the involved students' samples could not be done due to those differences. Hence, we cannot infer that the whole development process leads to a more effective TLS after each redesign phase.

Nevertheless, despite the above limitations, we think that the present study may contribute to science education research, at least in two areas:

1. Development of research-based TLSs
2. Science and technology integration

11.1 Development of Research-Based TLSs

This study provides a useful, complete example of how a TLS can be constructed, implemented, and redesigned, starting from a core that in some way characterizes it. To better refine the role of the core in the development process, as represented in the model of Fig. 12, the following points deserve some considerations. They concern the presented TLS which integrates science and technology, but they can be easily generalized to any TLS.

As a first aspect, we want to underline the importance of the choice of the content area. We have already justified the main reasons for the choice of the optical properties of materials. Here, we stress that this content area has been particularly suitable to elementarize basic physics contents related to light propagation and guidance. In particular, it was possible to address that some properties of matter (as the index of refraction) are at the basis of light behavior in materials. Moreover, it was shown how, from the driving theme chosen – the optical fibers – it has been possible to identify the phenomenon harnessed in that technological object – total internal reflection – and construct on such a basis the common core of concepts discussed in the TLS activity sequence. The results of the first and second study plausibly show that this whole reconstruction process was effective in addressing well-known students' alternative ideas (e.g., Palacios et al. 1989; Singh and Butler 1990) about these common core concepts.

Secondly, once identified, the common core concepts require a different pedagogical approach with respect to (w.r.t.) the case in which they are treated separately. The dialogue that introduced this chapter clearly shows that leftovers of past research and teaching habits (e.g., optical fibers as application of reflection and refraction laws, which implies a view of technology as applied science) may be difficult to overcome, on behalf of both researchers and teachers (Aikenhead 2003). In our case, the partnership initially focused prevalently on the geometrical optics contents and the related students' difficulties (e.g., vision), since the participants were all more acquainted with such contents. The optical fibers appeared only as application of these contents, as frequently done in most Italian textbooks. Similarly, references to epistemological issues as the science and technology relationships were very latent in the activities, if any. The preliminary version of the TLS clearly embedded this rather conservative attitude of the partnership. Only after the first trial in the pilot study and the analysis of collected data were carried out that the partnership recognized flaws in the science and technology integration as implemented in the TLS and began to fix different aspects and change specific parts of the TLS. Therefore, this study provides evidence of how the iterative design of subsequent cycles of implementation and data analysis may improve the process of reconstructing the driving theme to identify the common TLS core.

11.2 Science and Technology Integration

Our results plausibly prove that science and technology integration cannot be carried out by means of a straightforward process that brings together contents from the two fields or infusing some activities typical of one field in the other (e.g., taking design activities into science classroom); rather, it should be carried out through a thoughtful reconstruction process that elementarizes the science and technology components of a given starting theme. The evidence emerged from the analysis of the students' answers to the open question about science and technology relationships, an epistemological aspect that has received until now little attention (Constantinou et al. 2010; DiGironimo 2010), may clarify which features of this process have played a key role. Certainly, the scenario, introduced after the pilot study, was important to familiarize the students with an example of the science and technology interaction very close to their everyday experience (the Internet connections and the file sharing/downloading). However, a major role was plausibly played by the Unit 1 and 2 activities purposefully designed on the basis of the reconstruction process of the optical fibers theme. The effectiveness of such activities may be related to the fact that they explicitly show how the scientific description of a phenomenon (total internal reflection) in terms of mathematical quantities (index of refraction, laws of refraction, and reflection) may lead to harness such phenomenon in a technological object (the optical fibers) and to develop an entire new tree of related technologies.

Clearly, this study cannot say it all about the science and technology integrated approaches (Geraedts et al. 2006). For instance, we cannot still answer the question by Barak and Pearlman-Avnion (1999): who will teach such integrated programs? The teachers who implemented the TLS here presented were either experienced teachers or novice teachers trained to the contents addressed. Hence, we cannot infer if the proposed TLS can be taught by other teachers without specific training. Similarly, we have described the development process focusing only on one example content area, the optical properties of materials. In another content area, from where should this process start, science contents or technology applications? On what process should the teaching be more focused on, scientific inquiry or technological design? These questions deserve further attention on behalf of science and technology education scholars in order to improve the integration between these two content areas in school practice.

Appendices

Appendix A: Examples of Students' Worksheet

SW 1.2 Is It Possible to Make a Light Guide?

In this activity we will see that it is possible to construct, in the school lab, a light guide, and observe what happens when light travels along it.

Experiment: The Water Jet

Laser light is directed through the plastic tank filled with water and parallel to the tank base. The plastic tank has a hole from which water exits.

Figure A-1: Photo of the experimental setup for water jet experiment

1. Observe what happens if you hit the hole with the laser beam. Write down your observations

   The figure shows the experimental set-up. Sketch the light path from the laser source to the basin that collects the water.

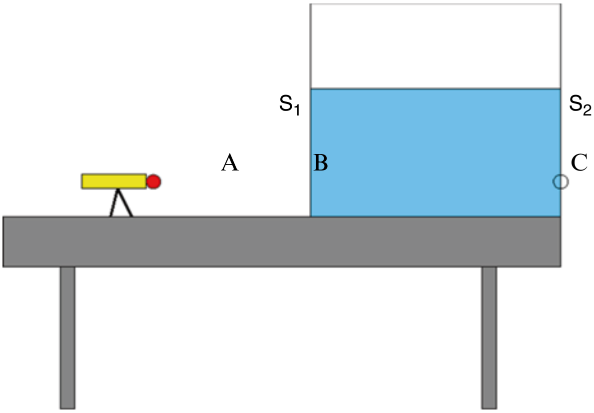


Figure A-2: Schematic representation of the experimental setup for water jet experiment

2. Now, focus your attention on the path of light in AB and BC.

   Describe what you observe.

   How is the light path when it travels in air (AB in the above figure)?[7]

   How is the path of light when it travels in water (BC in the above figure)?

   What conclusions can you draw?
3. Focus, now, on the light path in the water jet.

   Give a detailed description of what you see in the water jet.

   What conclusions can you draw?

SW 2.2 Optical Fibres' Characteristics

In this activity we will become aware that there is a maximum angle at which the light sent in the fiber propagates in the fiber's core; we will also investigate on the influence of core and cladding's refraction index on this angle. Finally we will study optical fiber's main characteristics and relate them to the materials' optical properties.

[7] To be able to see the laser beam in the air, "dirty" the air by adding some particles. In this way, you can see the path of light.

Experiment: Introducing the Acceptance Angle

Send the laser beam at the end of the glass bar and observe if the opposite end is lighted or not. Turn the laser and observe what happens as you change the entrance angle of light into the glass bar.

Do you always see the opposite end of the bar lighted?

Experiment: Role of the Cladding in Determining the Acceptance Angle

Dip half of the glass bar in a glass a water. Send the laser light at one end of the glass bar and remark if you see any difference when the glass bar is in air or in water.

The maximum angle for which you still see light at the opposite end of the bar is smaller or greater when the bar is in water or in air?

Computer Activity: Calculating the Acceptance Angle

Open the file "optical_fibre.fig"

1. Write down the value of the maximum angle θ_a for which you have total internal reflection in the core
   θ_{amax} = acceptance angle = ………………
   Write down $2\theta_{amax}$ = angular aperture = ………………
   What can you say about the light beams that enter the fiber at angles less or equal than $2\theta_{amax}$?
2. Let's investigate how and if θ_{amax} depends on the core's and cladding's refraction indices. Fix a value for the core's refraction index $n_n = 1{,}50$. Fix initially the cladding's refraction index to the value $n_m = 1{,}10$ and fill the table

θ_{amax} (°)	n_n	n_m	$n_n – n_m$
90	1,50	1,10	
	1,50	1,20	
	1,50	1,30	
	1,50	1,40	
	1,50	1,47	

How does θ_{amax} vary if the difference $n_n – n_m$ increases?

Appendix B: Italian Educational Context for Science and Technology Teaching at Secondary School Level

The TLS about optical properties of materials has been intended for the Italian syllabus (14–15 years old students). In order to understand why the proposed TLS deeply differs from usual approach, some details about the Italian educational system are worth discussing. In particular, since the topic of the optical properties of materials is in some way featured in well established parts of the Physics and of Electronics syllabi, some details about these subjects will be hereafter given.

These two subjects are exemplar of a separation between Science and Technology which commences at the beginning of the five-year upper secondary school stream when students are about 14 years old. This separation is long established in Italy, a country with centralised curricula and syllabuses decided by the Ministry of Education and without much local autonomy at school level. Since there has been no significant reforms in related curricula, Technology as a school subject is still mainly intended as "industrial arts" taught only in technical/vocational schools and 'de facto' clearly separated from science education, for instance in scientific lyceums.[8] Such separation could be one of the reasons for which Italian students do not hold an informed view about Science and Technology, as evidenced by many recent national surveys.[9]

Basic Physics is traditionally presented in secondary school in both lyceums and technical/vocational schools.[10] Some Technology contents are proposed as applications of scientific contents.

As it can be inferred, in Italian school curricula a blend of the "Technology as applied Science" and of the "demarcationist" views (Gardner 1994, 1999) exists. As a consequence, also the treatment of optics in textbooks follows such trend. For instance, in most of the physics texts for the scientific lyceum prevails the

[8] In the scientific lyceum stream, the general science education curriculum essentially involves biology, earth sciences, chemistry (from the first year on), and physics (from the third year on). In the technological/vocational stream, chemistry, biology, and physics are taught only in the first two years, whereas various technological subjects are taught from the third year on, according to specific sub-curricula (e.g., electronics, computer science, mechanics, electro-technical).

[9] The studies by the Science and Society Observa consortium (Arzeton and Bucchi 2009) have shown that about 30 % of Italian citizens have low-level knowledge about scientific and technological contents and are not interested or skeptical towards science and technology achievements. Although Italians value positively the effects of science (about 63 %), around 46 % think that science and technology have a baleful influence on Italian society's values. The vast majority of those interviewed (75 %) also think that the most important contribution that science can give to improve human life concerns is mainly in the area of medical applications. No reference to fundamental or applied research can be found in the interviewees' opinions. Although such views are more frequent among the older population with a low level of instruction, about 35 % of interviewees between 15 and 19 years share the same ideas.

[10] In scientific lyceums, physics is taught 2 or 3 h per week from the third year on, and in classical lyceums (more humanities-oriented), from the fourth year on. In technical/vocational schools, physics is taught for 4 h per week in the first and second years. Half of these hours are devoted to compulsory laboratory activities. An assistant specialized in technical subjects helps the teacher.

"Technology as applied Science" view; therefore, geometrical optics treatment precedes chapters about technology applications . In the textbooks for technical and vocational schools, the demarcationist view prevails. Optical Fibres, in particular, is addressed in the fourth year of technical schools within the 'Telecommunications" course. The focus is on technical characteristics and on the way to transmit data through optical fibres; the phenomenon at the core of their functioning (total internal reflection) is addressed at the beginning giving geometrical optics formulas.[11]

Appendix C: Teacher's Post Instruction Interview

Q1. So what do you think of the activities? Explain with some examples
Q2. What do you think of the optical fibre scenario as context? Have you experienced any difficulties in addressing it? Explain with some examples
Q3. What do you think of the students' worksheets? Explain with some examples
Q4. What do you think about the way to address geometrical optics? Did the students find difficulty? Explain with some examples
Q5. What do you think about the possibility to address aspects of Science & Technology? Explain with some examples

Appendix D: Students' Pre-Post Questionnaire

Item 1 According to your idea, is it true that

The index of refraction is a property of materials	YES	NO
To measure the refraction index of the water is necessary to measure the intensity of a light beam propagating in the water	YES	NO
The value of the refraction index of a substance depends on the quantity of substance	YES	NO
To measure the refraction index of a substance with respect to another, it is sufficient to know the critical angle between them	YES	NO
To measure the refraction index of a substance it is necessary to know its density	YES	NO

[11] The way of presenting optical fibers is very similar in all the textbooks used in this kind of schools (see, e.g., Bertazioli 1999; Tomassini 2004). First, light propagation in an optical fiber is discussed, focusing on total internal reflection and on the formula for the maximum angle (acceptance angle) at which such phenomenon happens for optical fibers. Then the various types of optical fibers are introduced (mono-modal, multi-modal, step- and graded-index), and their characteristics are discussed. Finally, dispersion and attenuation of the travelling signal are addressed, focusing on technical parameters as chromatic dispersion and band-pass coefficients. A presentation of the most used and commercially available opto-electronic transmitters' and detectors' parameters is also provided.

Item 2 According to your idea, is it true that

Light travelling from water to air can undergo total reflection	YES	NO
The critical angle between two materials depends only on the refraction index of the material in which the light is totally reflected	YES	NO
Light travelling from air to water can undergo total reflection	YES	NO
Total reflection is a phenomenon which occurs when light travels from a less refractive to a more refractive material	YES	NO
Given a light beam travelling from material 1 to material 2, the critical angle of material 1 with respect to material 2 is the smallest incidence angle for which there is no refraction in material 2	YES	NO

Item 3 In the figure D1, θ_0 is 45°. According to your idea, is it true that

If $n_2 > 1.40$ there is refraction between core and cladding	YES	NO
After entering the fibre, the beam deviates towards the fibre's axis	YES	NO
To know how the beam deviates after entering the fibre it is necessary to know n_2	YES	NO
After entering the fibre, the beam deviates towards the upper part of the fibre	YES	NO
It is sufficient that $n_2 < 1.40$ to have always total reflection between core and cladding	YES	NO

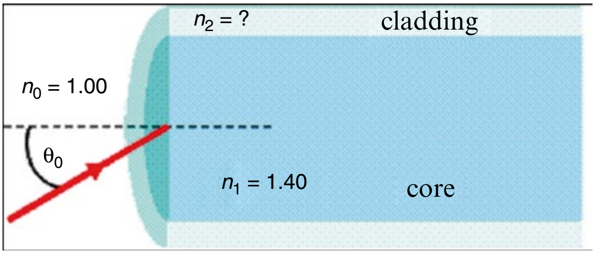


Figure D-1: Schematic representation of a ray entering into an optical fibre

Open Question: What are, in your opinion, the relationships between Science & Technology?

11.3 Appendix E Students' Post-instruction Interview

TASK 1 Given the situation the image E1, draw the rays of light in air according to their propagation in the water

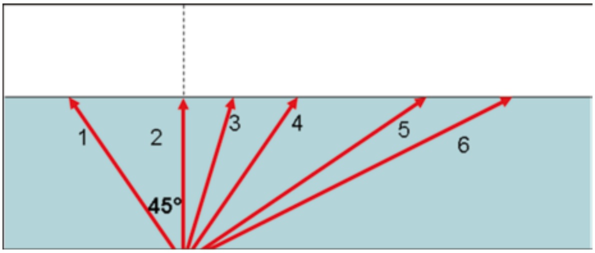


Figure E-1: Light rays propagating from water to air

TASK 2 Draw the laser beams as they travel through the materials in the figure E2 (n_{water} = 1.33; n_{oil} = 1.67).

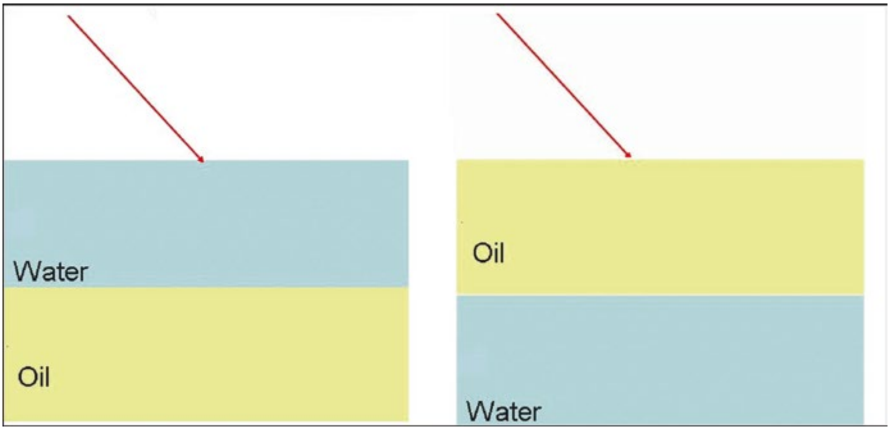


Figure E-2: Light ray propagating in media with different refraction index

TASK 3 A light beam enters a fibre made of a plastic transparent tube ($n = 1.57$) immerged in water ($n = 1.33$). Draw the light path when light enters in the fibre at an angle of 37.9° and at an angle of 52.3°. Briefly explain your answer.

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The Iterative Evolution of a Teaching-Learning Sequence on the Thermal Conductivity of Materials

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1 Introduction

Research on designing teaching-learning sequences (TLS) in science education has been going on for over two decades. The term teaching-learning sequence (TLS) is used to identify the potential construction of fruitful links between the designed teaching and expected student learning outcomes as a distinguishing feature of a research-based medium-scale curriculum development aiming at bringing research and teaching closer, in several contexts, than is the normal practice (Meheuet and Psillos 2004). From a more general pedagogical perspective, design-based research (DBR) also focuses on the relation of research to practical problems (e.g., Sandoval and Bell 2004). TLS and DBR approaches have the potential to contribute to the development of teaching and learning materials and strategies that are grounded in research evidence. Besides good products and processes, the development of an innovative intervention based on research results, such as a TLS, can and should contribute to existing theoretical and methodological knowledge, since the aim of design-based interventions in complex settings is to provide insights into contextualized theoretical knowledge (Design-Based Research Collective 2003).

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A TLS normally develops gradually out of several applications according to a cycling evolutionary process illuminated by research data. This process enriches the TLS with empirically validated student outcomes and contextual applicability. Such a design and development process tends to be iterative. Iterative development as a broad approach for developing and investigating authentic educational interventions is also suggested by works based on design-based research (Cobb et al. 2003). In this respect, iterative development is a common feature of works about TLS which originate from science education and design research which is based on a general pedagogical perspective.

In science education, design frameworks from various perspectives have been proposed to account for the design and validation of TLS (Lijnse 1995; Leach and Scott 2002; Duit et al. 2012; Andersson and Bach 2005; Kariotoglou et al. 2003). One of the main aims of such proposals is to provide frameworks for guiding the design of effective TLS, drawing on different psychological and epistemological grand theories. Despite their different focus, these proposals stress the need for cycles of implementation and dynamic feedback based on research data as a powerful heuristic tool for developing transparent and effective TLS. Although iteration is important for the development of a TLS, little is found about this process in the design frames or in empirical studies (Viiri and Savinainen 2008). This could be due to the craft knowledge of the researchers who take decisions on the evaluation and modifications of a sequence. As has been pointed out, "several publications have reported the design and evaluation of an innovative TLS on a certain topic, not many empirical studies have reported relevant details of the process of refinement of a TLS analyzing the different changes that this development process entails, and thus suggesting further ways to overcome the identified weak points or flaws of the designed sequence" (Meheuet and Psillos 2004). We consider that more in-depth studies are necessary to provide insight into how to refine a TLS so that development will be substantially based on research evidence. Thus, in the present paper, we take up the issue of iteration in the context of the development of a specific TLS and attempt to shed some light on its design and evolution "through careful documentation and retrospective analysis" (Kelly et al. 2008a).

In terms of scientific knowledge, the TLS in question aims at introducing secondary students to materials science, specifically at enhancing secondary students' understanding of thermal conductivity of materials. In terms of pedagogy, the TLS aims at introducing them to aspects of scientific inquiry, as discussed further on. Specifically, the scope of this paper is to present and discuss in detail the difficulties of students and teachers who were engaged in this innovative TLS and the strategy followed during the iterative cycle of gradually modifying the initial TLS1 towards an enriched TLS2 and subsequently to a final TLS3. These two sequences grew out of TLS1 through cycles of design, application, and research. Systematic documentation of this kind produces a design case that can be described in terms of case-study research (Yin 1994), which can promote a useful exchange of ideas in the research community and favors reflections about how an iterative cycle of design-enactment-evaluation-redesign affects the development of a TLS.

2 Background

2.1 *Introducing Thermal Conductivity of Materials*

Materials science deals with how materials are composed and structured, how structure determines a material's macroscopic properties, and how properties of materials relate to technological applications and provide means to solve particular problems. Materials science is an interdisciplinary field relating science to technology, with profound educational significance. It is concerned with inventing new materials and improving known ones by developing a deeper understanding of the microstructure-composition-synthesis-processing relationships (Callister 2006). From the point of view of introductory materials science, some of the properties considered most important are the thermal qualities of heat capacity, thermal conductivity, and expansion coefficient. Conductivity is an essential property of natural materials and advanced technology artefacts. The field of application of this property is widespread and involves ceramics and polymers, metals and alloys, composites, and related natural or synthetic materials, artefacts, and applications. From a social point of view, students and adults experience everyday phenomena related to conduction in situations like cooking, take decisions about using artefacts such as jackets, and encounter newly developed materials which, for example, affect heat loss at home, school, or work.

In this context, we consider it socially relevant and educationally significant to provide opportunities for compulsory education students to become familiar with aspects of materials science and specifically with thermal conductivity of materials.

2.2 *Inquiry as a Contemporary Framework for Teaching and Learning Science*

From a pedagogical perspective, research findings support the teaching of science as inquiry and advocate that students in compulsory education should have the opportunity to be involved in relevant activities and develop the ability to think and act in ways related to scientific inquiry (Abd-El-Khalick et al. 2004). Thus inquiry is conceived as both a process and an outcome, aiming at engaging students in investigating physical phenomena as well as several facets of scientific understanding. While several science educators suggest that inquiry-based approaches can be effective in facilitating students' conceptual, methodological, and epistemological knowledge and skills as well as their motivation and interest in science and technology, in most European countries, including Greece, actual science teaching does not pursue inquiry (EU 2007).

While inquiry teaching can take multiple forms, the approach can be seen as a continuum from teacher-led to student-led processes. This continuum usually includes the three most common strategies for teaching by inquiry: structured inquiry, guided inquiry, and open inquiry. Blanchard et al. (2010) note that the "degree of inquiry depends on who is responsible for the activity." According to Eick et al. (2005), the teacher should scaffold experiences – from highly structured to more open – by varying the amount of guidance, enabling students to come up with self-conceived conclusions. This gradual transition to greater student autonomy allows the teacher to remain in control while still providing the support and guidance needed by students who are new to inquiry learning. In the present paper, we adopt the view that there is "no optimal form of inquiry that extends across all content or context" (Blanchard et al. 2010).

Structuring can vary depending on the classroom context and aims of teaching. In the present study, we consider that one important issue not usually addressed in the literature is what constitutes a productive strategy for introducing traditionally taught students, who are the subjects of the present study, to inquiry in a conceptually rich topic such as conductivity. Many studies, moreover, focus on the conceptual domain rather than following an integrative approach to inquiry including methodological skills and epistemological awareness. This issue is also taken up in the present study in the design of TLS.

2.3 Identifying the Didactical Problem: The Present Case Study

The context of the study is the lower secondary school in Greece, which is called Gymnasium, is compulsory, and addresses students between 12 and 15 years. Physics is an individual subject taught in the second and third forms to students 13–15 years of age for 2 h per week. In most schools, science teaching is based on the traditional knowledge transmission model, focusing on conceptual knowledge and including some demonstrations and minimal, if any, experimental work.

One of the chapters in the Year Two Gymnasium physics textbook concerns "Heat and Temperature" and treats those concepts at macroscopic and microscopic levels; it also treats heat transfer, touching on the microscopic processes underlying heat exchanges rather superficially. While curriculum implementation is strict, special legal arrangements allow teachers to pursue an in-depth treatment of disciplinary and interdisciplinary themes, like conductivity, using extracurricular materials, in the "flexible zone" part of the school timetable of about 2 h per week.

In concluding the background of the study, we consider that teaching science as inquiry requires that the aims of instruction be shifted and broadened from a teacher-centered pedagogy to a more learner-centered one, which should aim at epistemological awareness and investigative skills as well as conceptual achievement. This is an important educational issue requiring innovative design and development.

Thus, in the present case study, we treat in depth the problem of developing and refining an innovative TLS introducing students to thermal conductivity and to inquiry that is applicable in the traditional setting described above.

3 Part 1: Overview of the Design and Implementation of a TLS on the Thermal Conductivity of Materials

3.1 Overview of the Design of TLS

At the design stage of TLS, the authors took into account several design decisions. At first, inspection of the entities, structure, and proposals made by several suggested design frames for TLS indicated that they focus on different aspects of designing a TLS, although there are certain common issues like adapting instruction to students' conceptions as mentioned in the introduction (Psillos and Kariotoglou). In this context, the authors decided to draw on several frames and other sources, taking into account that "when designing educational objects multiple theories and methods are relevant in order to explain, predict or make decisions" (Hjalmarson and Lesh 2008).

Second, the educational and social reasons for selecting thermal conductivity as the scientific content and inquiry as a contemporary fruitful approach for teaching and learning science were discussed (Sects. 2.1, 2.2, and 2.3). Moreover, the authors drew upon the design frames Model of Educational Reconstruction (MER) (Duit et al. 2012) and "content or domain specific theory" (Andersson and Bach 2005) for designing and developing the TLS.

Third, the role of teachers as well as of educational contexts is taken up and emphasized by the "domain-specific theory" frame. Concerning agency, the authors considered the development of a TLS as a participatory activity between researchers and teachers. The TLS was designed and developed collaboratively by a five-member group composed of two science education researchers, one researcher in solid-state physics, and two experienced teacher-researchers in science education (the working group (WG)). All authors were members of the WG. The WG collaborated closely with four experienced physics teachers, who implemented the TLS. The WG met regularly during the initial design and implementation stages, the aim being to integrate researcher knowledge and teacher experience. The collaborating teachers were familiarized with materials and participated in specific design meetings. Additionally, experts from abroad participated in the iterative development cycles, carrying out content analysis of the teaching materials produced by the WG.

Fourth, regarding educational context, the issue of the implementability of the TLS in the classroom, which is usually not discussed in TLS studies but in DBR ones, was taken into account, with examination of its practicality and relevance (Kelly et al. 2008a, 2008b). Practicality relates to whether this product may be realistically usable in school practice, relevance to whether its application will be feasible in regular Greek school settings. The WG considered that conductivity is not a perceptually obvious property of materials. Its comprehensive treatment requires some understanding of basic concepts relating to heat, study of factors and processes involved in the conduction of heat, and linking of macro properties with micro processes beyond the usual curricula treatment. The TLS should, therefore, refer to thermal conductivity as a complementary theme for extended curriculum activities following instruction on heat, temperature, and the corresponding kinetic model in the normal Greek curriculum; it should also provide for flexibility of instructional treatment by both teachers and students. Therefore, the WG decided to implement the TLS in the "flexible zone" towards the end of instruction on this chapter (Sect. 2.3).

Fifth, concerning a contextualized developmental strategy, the WG thought that it would be better to proceed stepwise in implementing this innovation, by designing and staging an initial core TLS1 with limited scope, since teachers and students in Greece are familiar neither with integrative inquiry teaching nor with an extended treatment of a demanding topic like thermal conductivity. As a result, it was decided that TLS1 should mainly focus on the conceptual domain with which teachers are familiar, enriched by technological applications. This would mean that students would not be involved in experiments, but emphasis on TLS1 should not be given to developing students' procedural and epistemological knowledge. Should the empirical results be positive, then TLS1 would be expanded in both goals and relevant activities. Thus, subsequent versions, i.e., TLS2 or TLS3, could target students' epistemological awareness and design of experiments in order to provide students with integrative inquiry experiences. Such a deliberate stepwise strategy for implementing TLS combines decisions based on thoughtful a priori evaluation of contextual conditions by experts with empirical data from applications (Sandoval and Bell 2004).

Sixth, MER is based on the hermeneutic tradition of curriculum development and links closely considerations on scientific conceptual structure with analysis of the educational significance of the content in question, as well as with empirical studies on students' learning processes. The WG drew on MER in order to develop the content for the TLS as a constructive endeavor taking into account both scientific knowledge and research on students' conceptions.

Finally, given that teachers in Greece are accustomed to a tradition of a standard compulsory curriculum and teaching units described in one book, the WG decided to develop TLS as a coherent treatment of conductivity in terms of content, structure, and educational activities, not as a loose source of activities and materials. The WG asked the teachers to creatively implement TLS1, TLS2, and TLS3 to their classroom contexts.

3.2 Goals of the TLS

Taking into account the above considerations, the WG set the following goals for the TLS.

Regarding conceptual knowledge, students should understand that some materials allow heat to be conducted much faster than others, be able to rank materials according to their thermal conductivity, understand that heat flow takes place between bodies and their environment until these come to a thermal equilibrium with it, interpret and compare conduction in insulating and in conducting materials at the microscopic level.

Regarding procedural knowledge related to experimental investigations, students should recognize and handle factors which affect thermal conductivity, acquire experimental design skills by simulated or hands-on experiments, be able to recognize and select conductors and insulators for use in everyday situations.

Regarding epistemological awareness, students should be aware of aspects of the nature and function of scientific models.

Regarding the technological domain, students should be able to apply their knowledge to treat and design technological applications related to conductivity in their everyday environment.

3.3 Students' Conceptions and Skills

Relevant research shows that students do not take into account all the parts of an interacting thermal system, often neglecting the surroundings in their explanations (Kesidou and Duit 1993). Several studies have shown that differentiation between heat and temperature constitutes a major difficulty for secondary students. Students have difficulties in understanding that when objects interact thermally, they come to a thermal equilibrium. They seem to be broadly familiar with "heat movement" but often do not focus on how heat transfer occurs or provide alternative explanations for transfer mechanisms in solids, liquids, and gases (Engel Clough et al. 1985; Sciaretta et al. 1990). Students also believe that materials that can insulate "hotness" are fundamentally different from materials that can insulate "coldness" (Lewis and Linn 1994).

At the microscopic level, research shows that even students in higher secondary education face difficulties in understanding the function and properties of microscopic models and linking them with macroscopic properties and phenomena. In the area of heat, an example of such a difficulty is the well-known belief in the warming of molecules when the temperature of a material increases and the diffusion of hot molecules during heat transfer.

Regarding students' mastery of design of experiments, assessment even at university level has indicated that they have limited understanding of the process and of such fundamental concepts as defining dependent and independent variables and distinguishing possible methods of measurement (Lefkos et al. 2011). Development of such mastery is considered an important skill for science education (Johnstone and Al-Shuaili 2001).

At the epistemological level, several studies have found that middle and upper secondary students have difficulties in understanding the nature of models, since they believe that models are copies of the real world and do not see that they are used to interpret or predict phenomena. Few students or even teachers treat models as a representation of an idea or theory, as a research tool, a construct which is tentative, may change and may be used for predicting phenomena. However, the question of how students can be helped to reason beyond the simple realistic view of the nature of models is an open issue (Treagust et al. 2002).

3.4 The Content of the TLS

Analysis of the literature reveals a scarcity of approaches that focus on heat conduction and seek to foster secondary students' deep understanding of macroscopic properties, underlying processes, and technological applications (Thomaz et al. 1997). Taking into account students' views, the aims of the TLS, and the nature of the scientific content, the WG decided to organize the content of the TLS both at the macroscopic and microscopic levels. Besides, one argument in research is that understanding of heat and temperature requires some understanding of relevant transformed microscopic models (Wiser and Amin 2001).

Briefly, heat transfer by conduction involves transfer of energy within a material without transfer of mass. When time is limited, heat capacity matters. Heat capacity represents the quantity of heat required to produce a unit rise in temperature for one mole of a substance. The rate of heat transfer depends upon the temperature gradient and the thermal conductivity of the material (Callister 2006). Thermal conductivity is a reasonably straightforward concept when one discusses heat loss through the walls of a house. Conceptually, thermal conductivity can be thought of as the container for the medium-dependent properties that relate the rate of heat loss per unit area to the rate of change of temperature. For heat transfer between two plane surfaces, such as heat loss through the wall of a house, the rate of heat transfer by conduction is as follows:

$$\dot{Q} = \kappa \cdot \frac{A}{d} \cdot (T_{\text{HOT}} - T_{\text{COLD}})$$

where Q is the rate of heat transfer; κ is the thermal conductivity of the barrier; A is the area of the barrier; T_{COLD}, T_{HOT} are the temperatures at the two sides of the barrier; and d is the thickness of the barrier. This is Fourier's law concerning the rate of heat transfer at the macroscopic level. The WG decided to include a qualitative treatment of factors affecting conductivity according to Fourier's law adapted to (for example, see Unit 4 in Table 1).

At the microscopic level, the thermal conductivity of a system is determined by how atoms comprising the system interact. There are no simple, correct expressions for thermal conductivity. In metals, thermal conductivity mainly depends on the electrical conductivity of the material. In non-metallic material, the phonons in the system are known to scatter. Thus, in a general case, thermal conductivity has two contributing parts, the electronic one (κ_e) and the lattice one (κ_L): namely, $\kappa = \kappa_e + \kappa_L$. In metals, the electronic part is far more significant; in ceramics, the lattice is more dominant.

Table 1 Content and structure of TLS1 (index for all tables: *S* students, *Te* teachers, *D* designers, *T* temperature, *TheCo* thermal conduction/-ivity)

Units and their content	Main intended learning objective	Domains	Teaching strategy	Main teaching activities
Unit 1 Introductory, familiarization with heat conduction in materials	Familiarize S with cooling in different materials and ability to rank them.	Conceptual	Structured inquiry verification	*S* engage in hands-on experimenting, investigating the cooling of equal quantities of water in cups made of different materials and ranking them.
	Be able to carry out experiments and use experimental evidence to decide on an everyday problem.	Experimental		
Unit 2 Heat conduction in ceramic (crystalline and amorphous) materials	Understand *TheCo* in ceramics, relating it to the processes taking place in the micro-world.	Conceptual	Structured inquiry	*S* interact with simulated microscopic models to relate changes in *T* with microscopic process in amorphous and crystalline materials of different density.
	Understand the effect of density in *TheCo* of ceramic materials.	Conceptual		*S* use the models but do not discuss models.
Unit 3 Heat conduction in metals and alloys	Understand the function of free electrons in *TheCo* in metals and be able to interpret it.	Conceptual	Structured inquiry	*S* study *TheCo* by an experiment and are involved in interpreting conduction by using micro models.
	Be able to rank metals and alloys according to their *TheCo*.	Experimental		
Unit 4 Factors affecting thermal conductivity: surface area and thickness	Understand the role of thickness, surface area in *TheCo*.	Conceptual	Guided inquiry	*S* carry out investigations in a simulated laboratory to answer how the wall thickness and surface area of a vessel affect *TheCo*. Simulated experimentation in both heating and cooling situations.
	Be able to reflect on handling and testing variables	Experimental		*S* carry out measurements, draw conclusions, and discuss the parameters affecting *TheCo*.

(continued)

Table 1 (continued)

Units and their content	Main intended learning objective	Domains	Teaching strategy	Main teaching activities
Unit 5 Thermal conductivity in composite materials	Understand the differences in the microscopic process of *TheCo* in ceramics, metals, and composite materials.	Conceptual	Guided inquiry	*S* use the simulated models in order to compare the microscopic process of *TheCo* in ceramics, metals, and composite materials
	Understand the role of air in *TheCo* in composite materials.	Conceptual		Virtual experiment for cooling: comparison of amorphous ceramics of different densities
Unit 6 Open investigation on thermal conductivity in materials	Be able to apply taught knowledge to rank everyday materials according to their *TheCo*.	Experimental Technological	Open inquiry	*S* engage in an open investigation on ranking materials. They discuss, reflect on taught knowledge and applications about composite materials, investigate *TheCo* coefficients of everyday materials in a data base (e.g., ceramic hob, tea pot, jacket, wall insulation), and rank them.

These complex models of conductivity are difficult for secondary students' and beyond an appropriate depth in the treatment of scientific knowledge. The same comments apply for relevant simulations. Visualization of microscopic models is important even necessary for facilitating students' understanding. In the TLS, educational reconstruction concerned simulated microscopic models that were specifically developed for the process of heat transfer in different categories of materials. Figure 1 illustrates the transformed scientific models. Rigid balls arranged in a matrix simulate the atoms in a lattice for a crystalline solid (left part), while small red balls represent the motion of the free electrons in a metal (right part). To enhance the connection between microscopic and macroscopic levels, the screen is divided into two parts, the macroscopic model (top) and the microscopic (structural) model (bottom).

In usual approaches, like the Greek curriculum, conduction is introduced through the broad concepts of conductors and insulators. The innovation in the TLS is that this approach is reversed. Ceramics and metals are the showcases that are treated in the initial units providing the experiential basis for introducing students to

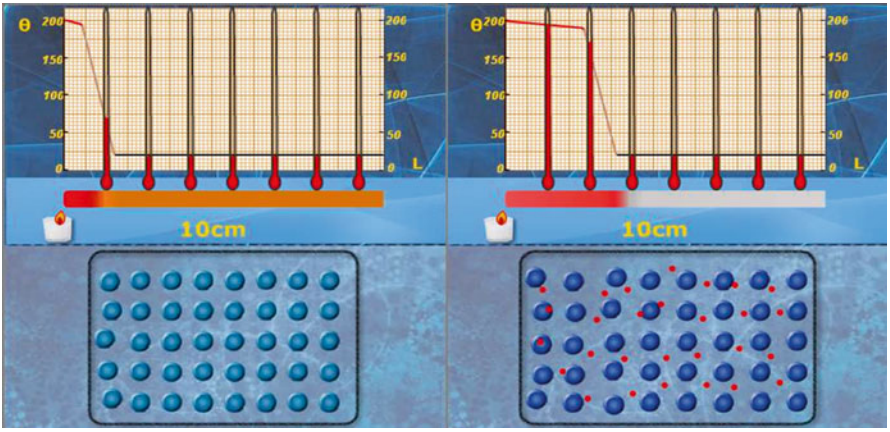

Fig. 1 A screenshot for thermal conductivity for a crystalline solid (*left*) and a metal (*right*)

conductivity. Thus, microscopic models of ceramics and metals are explored in the initial units in order to provide students with the conceptual tools for interpreting and understanding conductivity. The experimental study of factors affecting conductivity follows. The broad concepts of conductors and insulators are introduced later on in the sequence (see Table 4 further on).

In order to treat students' conceptions about the differential role of insulating, emphasis was put on several activities showing the equivalence between insulation that maintains "cold" temperatures and insulation that maintains "hot" temperatures. This is another innovation since such activities are not normally included in the Greek curriculum and elsewhere.

Finally, the present TLS was constructed as a combination of science and technology, using the latter for illustration and as motivation factor (Gardner 1994).

3.5 The Instructional Approach: Scaffolding Inquiry in a Traditional Context Embedded in an Enriched Environment

The framework adopted for teaching and learning in the present TLS is that of inquiry. Taking into account the discussion in Sects. 2.2 and 3.3, the contextualized inquiry strategy proceeds gradually from initial student involvement in structured inquiry towards guided and open inquiry (Eick et al. 2005). We consider that this approach constitutes an appropriate scaffolding for introducing traditional students to inquiry. The TLS consists of a range of activities structured in units which encompass different inquiry tasks; for example, Unit 1 involves structured inquiry tasks, and Unit 6 involves open inquiry tasks (see Table 4).

Students are helped to engage actively in inquiry, leading them to perceive learning as a constructive activity. They work in groups, solve problems, and engage in classroom discussion of the problem under study. They follow specially developed worksheets (WS) designed to help them identify their existing ideas, actively engage them in interactions with peers and teachers, and facilitate questioning and construction of meanings in a process taking place within the classroom community.

The inquiry approach is embedded in a rich environment including demos, hands-on and simulated virtual experiments and simulated models. Our approach of combining real and virtual experiments is based on the "real to virtual" strategy, which familiarizes students with multiple ways of investigating phenomena and enhances skills pursued in inquiry such as linking graphs (T, t) with phenomena (Sassi 2001). For example, students are first familiarized, in Unit 1, with graphs from hands-on experiments and in Unit 4, with real time graphs (T, t) in simulated experiments. An example of real demonstration consists of the well-known heating of a metal rod to which small balls are attached with wax. As heat propagates through the rod, the wax melts and balls start to fall one by one, and students are asked to predict, observe, and interpret results. For virtual laboratory work, we opted to use ThermoLab, which is an open learning environment suitable for studying thermal phenomena, and Flash-based simulated laboratories (Lefkos et al. 2011). A typical screenshot for the Thermolab is presented in Fig. 2a and that of Flash-based simulations, in Fig. 2b.

An important aspect of inquiry activities was the use of simulated microscopic models (Fig. 1) in an exploratory mode which we consider appropriate for introducing students to modeling (Petridou et al. 2009). Students are provided with the model, guided to look at its properties, discuss what these represent and then used by the students for visualizing thermal conductivity and interpreting experiments. Affordances for prompting and guiding observation and exploration of these models that allow students to visualize processes running over time are provided by WSs and software. For example, in an activity in Unit 3, students are asked to observe a simulation of a heated virtual metal bar (see Fig. 1, right) at one end, noting the conduction of heat through it by color change; notice the microscopic model for the

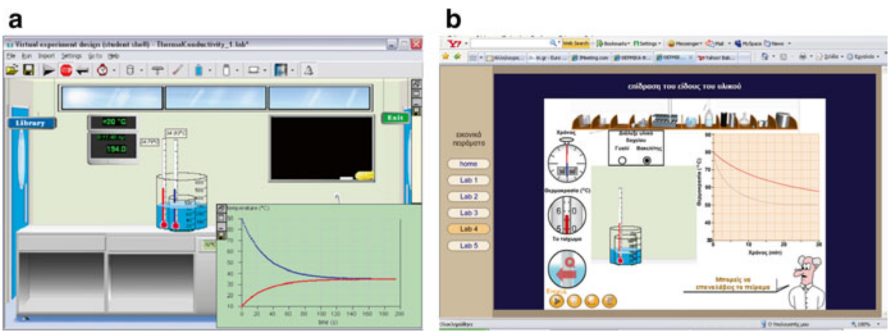

Fig. 2 (**a**) ThermoLab screenshot, (**b**) simulated laboratory

metals linked with the bar in the same screen; note the particles and the free electrons in the first and last columns; determine whether they oscillate or move in the same way; draw their own conclusions; and relate them to heat flow in the virtual bar in the same screen.

Finally, several tasks in the TLS are embedded in everyday life situations in order to motivate and engage students, including classification of materials according to their thermal conductivity and relating them to everyday use.

4 Overview of the Content and Structure of TLS1

TLS1 consists of six units of which Units 1, 5, and 6 are expected to take place in 1 teaching h and Units 2, 3, and 4, in 2 h. Unit 1 is a familiarization unit in which the students treat an everyday problem, carrying out hands-on experiments to provide answers and rank various materials. The concept of thermal conductivity is introduced in Unit 1. Units 2 and 3 deal with thermal equilibrium and thermal conductivity. Students study heat conduction at macro and micro level in ceramics and polymers, metals and alloys, carry out real and simulated experiments, explore simulated microscopic models and study the effects of changing T. In Unit 4, students investigate the factors/quantities affecting heat conduction. In Unit 5, they extend their study of conduction to composite materials. Several applications of insulating and conductive materials provide a framework for motivating students to study conductivity and contextualize their new knowledge in familiar everyday situations. Finally, in Unit 6, they engage in an open investigation concerning the choice and ranking of several materials set in a database according to their thermal properties, weight, and cost and reflect on previous taught knowledge.

An overview of the suggested content and structure of TLS1 is provided below in Table 1.

5 Overview of the Implementation of All TLS

Overall TLSs were implemented by four experienced physics teachers in the second year of Gymnasium, the compulsory lower secondary school in Greece. In each phase, before applying the TLS, these teachers read the relevant teacher's guide, discussed the aims and structure of the units with the WG, and went through various activities. The WG suggested that the TLS provides a comprehensive approach to thermal conductivity which should be applied creatively in their classrooms. Details of samples are given in Table 2.

Table 2 Description of sample for each TLS

TLS	School	Number of students	Year of implementation
TLS1 Teacher T1	One urban private school	20 students	2007–2008
TLS1 Teacher T2	One urban public school	Two classes, 47 students	2007–2008
TLS2 Teacher T3	One urban public school	One class, 24 students	2008–2009
TLS2 Teacher T4	One urban private school	One class, 24 students	2008–2009
TLS3 Teacher T4	One urban private school	One class, 25 students	2009–2010

6 Part II: Research-Driven Iterative Development

6.1 Research Questions

The present study is based on an interpretive qualitative approach to examine the facets of iterative development of a TLS. Retrospective analysis of the modifications and the reasons for them was carried out. This process involved reflection on key decisions taken and the relevant evidence and identification of the meaning of these modifications in relation to the goals and the theoretical perspective governing the designing of the TLS. The research questions were as follows:

1. What were the deficiencies noted in the various versions of the innovative inquiry-based teaching-learning sequence concerning thermal conductivity in materials that was applied in a traditional lower secondary education context?
2. What were the modifications for improving the TLS in order to make it more effective and feasible on the basis of empirical evidence?
3. What was the impact of these modifications on students' understanding of thermal conductivity?
4. Are there general suggestions concerning the development and implementation of teaching-learning sequences?

6.2 Sources of Data

The present study used different sources of data: questionnaires completed by the students before and after the implementation of each TLS, students' interviews, teachers' personal notes which included comments on the content of the TLS and the difficulties they encountered when implementing the various innovations of the TLS, students' worksheets, and recorded classroom discussions. Additional data were selected during oral communication between teachers and the WG and from post-instruction interviews with teachers. Valuable comments and suggestions on the content and activities of TLS were made by a sample of questions used is presented in the Appendix.

6.2.1 Monitoring Students' Understandings

1. *Conceptual understanding*

Students' conceptual development was investigated by pre/post tests in all TLSs. Specifically designed questionnaires were used, the pre-level ones comprising six open-ended and multiple-choice questions about events and everyday experiences (a sample is given in the Appendix). The post-implementation questionnaire included the original questions plus additional ones concerning the new issues introduced (10 questions altogether). Students were asked to substantiate their answers. Their ideas on different issues were investigated: thermal equilibrium and insulation, ranking materials by thermal conductivity, heat conduction through matter, microscopic processes of heat conduction, the role of the parameters of surface "area" and "thickness," temperature and thermal conductivity of materials, and interpreting a graphical representation of a verbally described thermal phenomenon. In addition to the questionnaire, semi-structured in-depth interviews with selected students were used; these focused mainly on clarifying answers to the questionnaire.

Students' answers to questionnaire and at interview were qualitatively analyzed. The procedure used identification of regularities in the first stage followed by a constant comparative technique.

2. *Development of experimental skills*

To assess students' ability to design experimental investigations, one open written task was used and interviews on the same task were conducted. To evaluate students' mastery of designing an experiment, we used a frame including seven specific dimensions of experiment design, namely, formation of hypothesis, description of experimental procedure, separation of variables, handling of variables, initial conditions, choice of devices and instruments, device settings as detailed elsewhere (Hatzikraniotis et al. 2010). In the evaluation process, acceptable responses were separated from unacceptable ones for each student individually, using a three-level qualitative scoring scale, the three levels being "missing-partially stated-completely stated". The same dimensions were also used in the individual interviews for evaluating students' answers. Questionnaire and interviews were used only after the implementation of TLS2, for school-based administrative difficulties and before and after the implementation of TLS3.

3. *Epistemological awareness*

Students' ideas about models were investigated using a written questionnaire comprising open questions focusing on three aspects of models: nature and function of models and model change. Semi-structured interviews provided additional data. In the evaluation process, acceptable responses were separated from unacceptable ones for each student individually, using a three-level qualitative scoring scale for each of the three aspects as detailed elsewhere (Petridou et al. 2013). Questionnaire and interviews were administered after the implementation of TLS2 and before and after the implementation of TLS3.

6.2.2 Monitoring the Implementation of the TLS in the Classroom

These data were taken in order to gain insights into the “classroom reality” and the feasibility of the TLS and included remarks by teachers and semi-structured post-lesson interviews on problems identified during instruction, including the handling of the activities and their suitability for their school settings.

6.3 Data Analysis and Modifications

Specific modifications aiming at improving the TLS after each application were performed by the WG. One issue that appears in the literature concerns the grain size of reported modifications in a TLS, whether it will focus at the fine grain level of a single activity, a group of activities or concepts embedded in a whole unit or several units or largely at a whole sequence. In the present work, the level of granularity of modifications varied from a single activity to groups of activities in WSs supporting common objectives running through one or more units. We characterize the level of granularity of our approach as “medium,” for example, in TLS2, inserting meta-cognitive activities in Unit 4 and Unit 5 aimed at enhancing students’ epistemological awareness, new activities enhancing experimental design in Units 4 and 5 in TLS2, replacing a whole Unit 6 from TLS1 to TLS2 when justified by evidence as detailed in Sect. 7.

The WG accepts that any modification may affect students’ learning but suggests that the effect of certain modifications is more pertinent to some learning objectives than to others, for example, the introduction of a new demonstration experiment in TLS2 aimed at helping students visualize the difference in conductivity of ceramics and metals, which is related to conceptual understanding rather than the development of skills in experimentation. Depending on the character of each activity, the modifications were organized in four domains related to the goals and design of the TLS: conceptual related to concepts and models, procedural related to experimental skills, epistemological related to the nature of models, and technological related to technological applications. In addition, certain modifications are linked to the criterion of relevance and practicality of the TLS, e.g., the duration of a WS.

To classify the modifications, a constant comparative technique was used; each of the compiled modifications was compared to the rest, and similarities and differences were identified. The data and modifications in these domains are organized,

Table 3 Categorization of evidence-based modifications

Units	Evidence-based modifications: perspective of the designers	Reasons and sources of data: students' understandings and teachers' views	Domains: Conceptual Epistemological Procedural Technological

as illustrated in Tables 3 and 5 further on, which present the links between data, decisions, and objectives. Due to limited space, we will present only representative examples of problems and modifications.

7 The First Iterative Cycle: A Retrospective Account of Modifications from TLS1 to TLS2

We herein mention that the modifications in the first iterative cycle are twofold. Modifications related to the conceptual domain and technological applications were based mainly on empirical data from implementation of TLS1. However, following the stepwise design strategy mentioned in Sect. 3.1, modifications related to the epistemological and procedural domain were deliberately implemented not in TLS1 but in TLS2 by WG taking into account the relevance, practicality, and potential for enrichment of TLS1 after its implementation. In discussing the flaws and modifications in the various domains, we keep a similar order in the present and next sections.

7.1 Identification of Flaws and Modifications Related to the Conceptual Domain

The modifications related to the conceptual domain relate to the main concepts dealt with by the TLS, namely, "heat" and "temperature," and the factors that affect conduction.

7.1.1 Identification of Flaws and Induced Modifications Related to Temperature and Heat Conduction

7.1.1.1 Objectives

With regard to temperature (*T*), the main objectives include students' understanding that a rise in the temperature of an object results in the agitation of its particles due to increased kinetic energy. With regard to heat (*Q*), the main objectives concern students' understanding that some materials allow heat to be conducted much faster than others and their ability to interpret and compare thermal conduction in ceramics, metals, and compounds at the macro/micro level.

7.1.1.2 Activities in TLS1

As mentioned in Sect. 3.1, the kinetic model of temperature and heat transfer was considered known to the students and, therefore, was not treated in TLS1. The interpretation of the process of heat conduction was introduced to the students in Units 2 and 3 of TLS1, in which they worked with microscopic models of crystalline and amorphous metals and alloys (see Table 1).

7.1.2 Problems and Difficulties: Students' Understandings and Teachers' Views

Table 4 presents the findings for the total number of students who participated in the implementation of TLS1, i.e., 67 students (see Table 2). In the pre- and post-tests, there were no differences between the three classes, so all data have been pooled together. The students' answers in the questionnaire were classified in four issues, and the results are presented in summary.

We note that there was progress concerning students' understandings of thermal equilibrium and explanations of thermal conduction and that a considerable percentage (40 %) could distinguish the microscopic process of conduction in conductors and insulators; the majority, however, showed no evidence of understanding these issues. Several well-known alternative ideas were identified, such as the heating of molecules and the transportation of matter.

The teachers confirmed that the students had difficulties in handling the kinetic model of temperature and in differentiating the various particle models used in Units 2 and 3 and agreed that the treatment of alloys was too advanced for their students. This view was also corroborated by the external experts.

7.1.3 Flaws and Evidence-Based Modifications: Perspective of the Designers

Taking the above results into account, the WG considered that the content and structure of Units 2 and 3 should change substantially so as to provide students with rich interactive activities to help them employ in an exploratory manner the simulated kinetic model of temperature in both ceramics and metals (Petridou et al. 2013). This should take place in a single unit, namely, Unit 2, in order to facilitate multiple treatments of the micro models; similarly, conduction in these two types of materials in relation to the temperature changes should be included in another unit, namely,

Table 4 Students' conceptual understandings before and after TLS1 ($N=67$) and TLS2 ($N=48$)

Issues	TLS1 Pre	TLS1 Post	TLS2 Pre	TLS2 Post
Thermal equilibrium of bodies and their environment	1.5 % gave acceptable answers.	23 % acquired the main idea of thermal equilibrium of bodies and their environment	4 % acceptable answers	54 % gave correct answers and acceptable explanations. The rest gave incorrect or alternative answers and explanations.
Microscopic explanation of *TheCo* through matter	3 % used the microscopic explanation.	32 % used microscopic explanations. Several were partially correct.	3 % used the microscopic explanation.	67 % gave acceptable explanations. The rest used microscopic explanations and gave *partially accepted explanations*.
The microscopic process of *TheCo* in different categories of materials	No pre-test: different materials were introduced during instruction.	40 % acceptable answers (correct matching). 60 % did not distinguish differences in *TheCo* process corresponding to different materials.	4 % refer to the "building blocks" of matter as a mechanism for *TheCo*.	63 % gave explanations using microscopic processes. Within this percentage, 21 % gave accepted answers and 42 %, partially accepted. 33 % attributed *TheCo* within the material to its good thermal conductivity. 4 % gave no reply.
Ranking materials depending on their *TheCo*			31 % accepted.	58 % accepted scientific. 42 % presented alternative answers.

Unit 3, in order to facilitate comparisons and differentiations (see Fig. 1). Table 5 presents the above and other modifications not discussed for brevity in Units 2 and 3, e.g., density.

Details of all the changes made in TLS1 and the reasons for them are shown in Table 5. The first column identifies the Units, the second records the main modifications carried out in each unit, the third outlines the evidence that led to each modification, and the fourth relates the modification to the domains.

Table 5 From TLS1 to TLS2

Units	Evidence-based modifications	Reasons and source of data	Domains
Unit 1	Modification of experimental procedure drawing on POE pattern.	Evidence from *Te* that *S* carry out experiments but do not recognize the steps of an experimental procedure	Experimental
Unit 2	**Change of content and activities**		
	New content added concerning the kinetic model of *T* and new activities in which *S* explore and compare micro simulated models for T, ΔT both in ceramics and metals	Evidence from *S* that kinetic model of *T* is not understood	Conceptual
	Content and activities concerning macro and micro treatment of *TheCo* in ceramics (crystalline, amorphous) and metals are removed from the original Unit 2 in TLS1 and spread to Units 3 and 4 in TLS2.	Evidence that *S* do not relate macro and micro and ignore differences between models	Conceptual
	Models of amorphous ceramics are removed.	Evidence from *S* and *Te* that models of amorphous ceramics complicate the concepts rather than simplifying them	Conceptual
	Activities about the effect of density are removed from Unit 2 to Unit 5.	Evidence from *S* that they do not comprehend density as affecting *TheCo*	Conceptual
	Order of activities was modified so that experimental work precedes simulations on *TheCo*.	Evidence from *Te* that activities on density are too demanding at this stage	Experimental
	New activities in which *S* use the models and discuss and reflect on their features stemming from their use. Discussion of theoretical aspects of models	Verification of practicality and relevance of TLS1. Gradual implementation of epistemological activities according to design	Epistemological

Unit 3	Models of alloys are removed.	Evidence from *S* and *Te* that models of alloys complicate the concepts rather than simplifying them. Handling composite materials at a micro level was demanding.	Conceptual
	Content and activities concerning macro and micro treatment of *TheCo* in ceramics (crystalline, amorphous) and metals are removed from the original Unit 2 and in Unit 3. Rearrangement and new activities in which S relate *TheCo* to ΔT. *S* compare differences in ceramics and metals by interacting with macro and micro simulated models of *TheCo*.	Evidence from *S* that they do not relate macro and micro and differences between models	Conceptual
	New activities in which S use the models and discuss and reflect on their features stemming from their use Discussion of theoretical aspects of models	Verification of viability of TLS1 and gradual implementation of epistemological objectives as planned by WG	Epistemological
	New exemplary demonstration experiment, the drop of wax, concerning TheCo of two different materials: ceramics and metals	Moderate comprehension of conductivity by *S*	Conceptual and experimental
Unit 4	New demonstration of the “metallic rods” experiment, focusing on the experimental technique for identifying the differential *TheCo* in metallic materials. Discussion of the demonstrated experimental methodology	Evidence from *S* and *Te* that students carry out experiments but do not recognize the steps of experimental procedure *D* introduce a new experimental technique.	Experimental
	Modification of the approach to students’ instruction for hands-on experimentation with the “metallic rods” experiment concerning the design and carrying out of an experimental process aiming at creating a hierarchy of five different metallic materials depending on their thermal conductivity and enrichment with reflection on experimentation	Verification of usability of TLS1 and gradual implementation of objectives concerning design of experiments as planned by WG.	Experimental

(continued)

Table 5 (continued)

Units	Evidence-based modifications	Reasons and source of data	Domains
Unit 5	**Change of content and activities**		
	Abandoned amorphous ceramics	Evidence from both *S* and *Te* that the distinction between amorphous and crystalline ceramics complicates rather than simplifies the concepts. Handling both types of materials at a microscopic level was demanding.	Conceptual
	Modification of instructions for cooling experiment in order to help S design new experiments on posed questions		Experimental
	New experimental activity of the effect of the density on *TheCo* in metals as a counter example of the effect of density on *TheCo* in ceramics	Evidence from S that they extend the contribution of the density in *TheCo* in ceramics to metals.	Experimental and technological
Unit 6	**Change of content and activities**		
	Abandon the investigation involving ranking of materials for special purposes such as …..		Technological
	Rearrangement and reduction of activities from UNIT 4/TLS1 related to factors affecting *TheCo* so a reflection on experimental methodology would be more targeted.	*Te* suggest that the “ranking of materials” investigation is not motivating and rather demanding.	Experimental
	Simulated experimentation concerns both heating and cooling situations.	Following viability of TLS1 gradual implementation of objectives about experimental design as planned by WG.	Experimental
Unit 7 New	New guided reflective discussion by *S* on all factors affecting *TheCo*.	*S* moderate overall achievements, WG decides to enhance reflective activities as a means towards scientific understanding.	Conceptual
Unit 8 new	New introduction of a scenario “For a Green house” involving open investigation in which *S* state the purpose then define and investigate the effects of variables and propose ways for reducing heat losses and saving energy in a house. Focus on common everyday materials, where the role of the air as an insulator is obvious.	Moderate appeal of “ranking of materials” investigation	Experimental
		WG decides to implement more open and motivating investigation linked to technological application.	Technological

7.2 Identification of Flaws and Induced Modifications Related to the Epistemological Domain

7.2.1 Objectives

The main epistemological objective added in TLS2 was enhancement of students' awareness concerning the nature, aims, and change of models.

7.2.2 Modifications: Perspective of the Designers

The transition from simply learning with models to learning about models by engaging students in discussions about the nature, aims, and change of models was considered by the WG and suggested in the literature as a higher level demand. As mentioned in Sect. 3.1, the WG decided that such modifications should be gradually introduced in the later versions of the TLS, namely, TLS2 and TLS3, should TLS1 prove practical and relevant (Sect. 7.5). Thus, the WG decided to enrich Units 2 and 3 by adding activities as Table 5 presents, for example, the students had to discuss and answer "in what way were the simulated models helpful for you?"

7.3 Identification of Flaws and Induced Modifications Related to Procedural Domain

7.3.1 Objectives

In TLS1, students were involved in experimental activities aiming at developing their ability to carry out hands-on and simulated experiments, constructing knowledge, and using experimental evidence to resolve an everyday problem.

7.3.2 Activities in TLS1

Experimentation in TLS1 was based on structured and guided activities and hands-on and simulated experiments embedded in WS, as presented in Sects. 3.5 and 4 and in Table 1.

7.3.3 Problems and Difficulties: Students' Understandings and Teachers' Views

Given the students' lack of experience with experimental work, it was essential for the implementation of TLS1 that they react positively to engagement with experimental and inquiry activities. Remarks made by teachers during teaching and in interviews and by students confirmed student engagement and positive reaction. However, teachers noted that several students carried out some activities with less than full understanding, for example, they were unclear about the meaning of simulated experiments involving both heating and cooling situations in Unit 4.

7.3.4 Flaws and Evidence-Based Modifications: Perspective of the Designers

The WG evaluated the above remarks as supporting the usability of inquiry activities and that students and teachers could manage to cope with more open experimental inquiry activities. In TLS2, students were allowed more time to reflect, discuss, and "think about science" while "doing science" so that they do not form the idea that inquiry is solely procedural in several Units such as 1, 4, and 5 (Table 5). In addition, in TLS2, students were gradually introduced to the experimental design, which was considered by the WG and suggested in the literature as an important higher level demand. New activities were introduced in TLS2, such as the exemplary "metallic rods" experiment, while certain modifications took place, as shown in Table 5. For example, in Unit 4, the teacher and/or the WS sets the problem and the students design the experimental investigation; quoting from the WS, "we have 5 metallic rods. How can we find, using an experiment, which one is the most heat conductive? What procedure do you suggest we should follow?"

7.4 Identification of Flaws and Induced Modifications Related to the Technological Applications Domain

We comment briefly in this section for reasons of space. Several students did not find the open investigation on thermal conductivity in solid materials interesting, while others were rather confused. Teachers were positive for relating science to technological applications, but it would be better for students to see everyday materials in front of them.

The WG decided to keep and enhance various technological applications throughout the TLS but to abandon the above investigation and replace the whole of Unit 6. Towards the end of TLS2, the new Unit 8 engages the students in a scenario seeking a solution to a technological problem concerning study of the insulation of an energy-saving house called the Green House. The WG thought that treating the Green House at the beginning of the TLS would guide students to deal with composite materials before studying less complicated ones like ceramics and metals. Besides, Unit 8 is based on an open investigation by students, so this structure complies with the design principle of gradual involvement in open inquiry.

7.5 Identification of Flaws and Induced Modifications Related to the Relevance and Practicality of TLS1

7.5.1 Objectives

The objective for TLS1 was to be practical or usable in the Greek context and relevant to the students.

7.5.2 Problems and Difficulties: Students' and Teachers' Views

There were several student and teacher comments in interviews as well as during the course of implementation. Relevance of TLS1 was evaluated by monitoring student engagement and motivation. Both teachers reported that the students managed to cope with this innovative environment, engaging actively in carrying out the WS activities during the real and the simulated experiments and exploration of the microscopic models; they also exchanged different roles and recorded and discussed results both within their groups and in whole class.

> T2… it is very important that students participated, I mean, I did not say to them do this do that, look at this. The students themselves were working and were noting what happens. I mean, the students used the Worksheets and would say to me: "Sir, we are going to see how heat is transferred in ceramics" and I would reply: "Well, see it".

They also noted that often, during teaching, several students would talk about materials and conduction and that this was more motivating than usual physics classes.

Concerning the practicality of TLS1, both teachers stated that they had followed almost all the activities and agreed that the application of TLS1 was feasible for the Greek school setting as an enrichment of curriculum in the context of the "free zone." However, it appeared that there were too many activities for the time available, implying that at times, both teachers and students were rushing to complete them and had no time to discuss the ultimate aims of these activities and evaluating the results:

> *R*. … So what do you think of the TLS and the activities?
> *Te1*: Well I think the experiments and the simulations helped students… you know to understand what happens… there are several activities… many teachers would be cautious about implementing the TLS simply because there are so many activities
> *Te2*: sometimes it is hard for the students to follow the activities and write down… too much writing.

The teachers also reported that at times, they preferred to prompt students to finish all the planned activities rather than attempt the creative adaptation of the activities on the WS.

7.5.3 Flaws and Evidence-Based Modifications: Perspective of Designers

Although reactions concerning timing and WS overload were unexpected, the WG decided to reduce the length and embedded requirements of all the WS. This would allow time for discussion during which students should be guided to discuss and reflect on the activities and construct their meaning in relation to theory. Besides, a whole new Unit 7 was developed, as shown in Table 5.

8 The Second Iterative Cycle: A Retrospective Account of Modifications from TLS2 to TLS3

8.1 *Developing TLS2*

TLS2 contained all the modifications mentioned previously in structure and activities, as well as an extensive teachers' guide including the goals, student' views, aspects of the scientific background on conductivity, instructional approach, and suggestions, as well as tests and a rubric for student assessment. For reasons of space only, a summary of the content of the units is illustrated in Fig. 3 and Sect. 9.

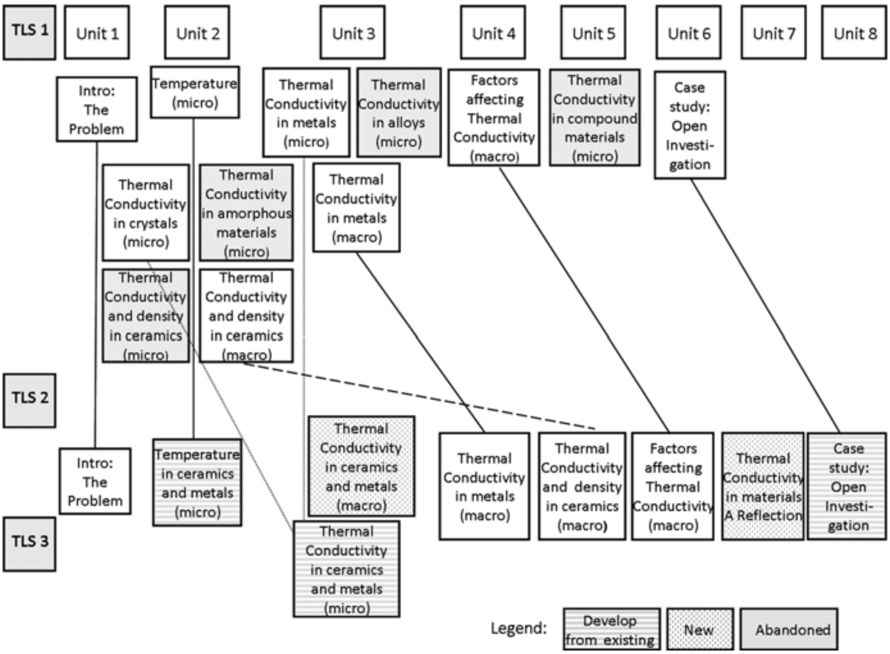

Fig. 3 An overview of the implemented conceptual modifications

8.2 Identification of Flaws and Induced Modifications Related to the Conceptual Domain

8.2.1 Identification of Flaws and Induced Modifications Related to Temperature and Heat Conduction

8.1.1.1 Objectives

As in TLS1.

8.1.1.2 Effects of Modifications, New Problems and Difficulties: Students' Understandings and Teachers' Views

The findings of the students' assessment before and after the implementation of TLS2 are presented in Table 4. There were no differences between classes, so data were pooled together. It is evident that there was noticeable improvement in students' understanding; the pre-implementation test results were similar to TLS1, but there was considerable progress in post-tests and achievements in all issues were higher than in TLS1, for example, 67 % of the students provided acceptable explanations in which they used microscopic processes after TLS2, while after TLS1, 60 % of them did not acquire appropriate knowledge of the microscopic thermal conduction processes. Results from the questionnaires were verified by the interviews with the students. For example:

R: Do you remember… what will happen if you stir the hot water in a pan with a metal spoon

S: It will burn you. Because metal is (a) conducting (material) heat flows quickly inside

R: ok! When you say it will burn you, what will happen ? If we had a huge (microscope)….

S: (interrupting) cause in metals there electrons which help quick movement.

Well when a metal is heated molecules vibrate and together with electrons which move add to the conduction of heat faster.

However, both teachers reported that students continued to have difficulties in distinguishing the structure of crystalline and amorphous materials. This distinction created confusion in the students, and the external experts suggested that it was too demanding for them.

8.2.2 Flaws and Evidence-Based New Modifications – The Perspective of Designers

The WG decided to remove the microscopic model of amorphous materials from Unit 2 in order to let students focus on the simpler structure of crystalline models and avoid engaging them with difficult and subtle distinctions of microscopic structures.

Table 6 presents an overview of the suggested structure and content of TLS3, following the above and the subsequent modifications. The structure of TLS3 is similar to TLS2, with differences only in the specific activities within the various units.

Table 6 Content and structure of TLS3

Units and their content	Main intended learning objective	Domains	Teaching strategy	Main teaching activities
Unit 1 Introductory, familiarization with heat conduction in materials	Familiarize *S* with cooling in different materials and be able to rank them	Conceptual	Structured inquiry verification	*S* engage in hands-on experimenting, investigating the cooling down of equal quantities of water in cups made of different materials, and ranking them
	Be able to carry out experiments and use experimental evidence to decide on an everyday problem	Experimental		
Unit 2 Temperature and the micro-world	Relate the changes in temperature with the processes taking place in the micro-world. *S* study and compare a microscopic model for temperature in ceramics and in metals	Conceptual epistemological	Structured inquiry	*S* interact, explore, and compare simulated microscopic models for temperature only in ceramics and metals.
				S work in groups in order to become familiar with and explore simulated microscopic models
Unit 3 Heat conduction in ceramic materials and metals	Make sense of macroscopic phenomena by bridging them to processes taking place in the micro-world	Conceptual	Structured inquiry	*S* watch a demonstration experiment on wax melting on ceramic and metallic rods and discuss results and methodology
	Understand the role of models	Epistemological		*S* interact with, explore, and compare simulated microscopic models for TheCo in ceramics and metals

(continued)

Table 6 (continued)

Units and their content	Main intended learning objective	Domains	Teaching strategy	Main teaching activities
Unit 4 Thermal conductivity of metals	Understand *TheCo* in metallic objects	Conceptual	Guided inquiry	*S* watch a demonstration experiment on *TheCo* in metallic rods and discuss technique
	Rank various metallic objects	Conceptual experimental		*S* plan and discuss an experimental investigation to investigate *TheCo* of four metallic rods
	Be able to interpret the experimental result by using the microscopic model and draw on the use of conductors in house and everyday situations	Conceptual experimental		*S* rank the four different metallic materials based on experimental evidence and reflect on methodology
Unit 5 Thermal conductivity of ceramics	Understand the relation between density and *TheCo* in ceramic materials	Conceptual experimental	Structured and guided inquiry	*S* carry out an investigation on cooling in different virtual vessels in a simulated laboratory and watch and discuss real-time graphing
	Be able to design and perform an experimental investigation to solve a problem	Experimental		*S* rank ceramic materials according to their *TheCo*
	Be able to find out answers to everyday situations in house concerning heating or cooling materials	Conceptual experimental		*S* design an experimental procedure to investigate the relationship between density and *TheCo* in ceramic materials
	Be able to draw on the use of insulators in house and everyday situations and for heat loss	Experimental conceptual		*S* plan and execute an experimental investigation to verify or reject a hypothesis

(continued)

Table 6 (continued)

Units and their content	Main intended learning objective	Domains	Teaching strategy	Main teaching activities
Unit 6 Factors that affect heat flow – thickness	Understand how thickness and surface area affects *TheCo*	Conceptual experimental	Guided inquiry	*S* study the effect of thickness of material in *TheCo*: design and carry out an investigation in a virtual lab on how the thickness of the walls of a vessel affects *TheCo*
				Experimental handling and discussion of surface area
	Be able to decide on an everyday problem from experimental evidence	Experimental		Simulated experimentation in both heating and cooling situations
Unit 7 Thermal conductivity of solid materials	Understand and relate all factors affecting the *TheCo* in materials	Conceptual experimental epistemological	Reflective discussion	*Te* and *S* discuss and reflect upon concepts, models and all factors affecting *TheCo*
Unit 8 For a green house	Form and test a hypothesis on an everyday problem	Experimental	Open inquiry	*S* watch and become familiar with thermal photography technique
	Be able to choose materials for thermal insulation	Conceptual experimental		*S* explore the use of everyday technological artefacts in house insulation
				S apply their taught knowledge and explore thermal insulation for an energy-saving green house

8.3 *Identification of Flaws and Induced Modifications Related to the Epistemological Domain*

8.3.1 Objectives

Students' awareness concerning the nature, purpose, and change of models was added.

8.3.2 Problems and Difficulties: Students' Understandings and Teachers' Views

Following implementation of TLS2, the results of the final written assessments and interviews showed noticeable understandings and considerable student awareness. For example, the following extract from an interview shows that some students were able to distinguish the structure of ceramics from metals, having gained awareness of the nature of models and their function as interpretive tools

R: (Shows picture similar to Fig. 1) Which material is ceramic and which is metal?
S: The metal is (shows the correct Figure). [T]his with the electrons and the other is ceramic
R: Why?
S: We have learned that in metals there exist electrons
R: What represents the electrons?
S: E… the small balls.
R: And the big ones?
S: E… the molecules.
R: Good! Are the molecules like balls?
S: No, this is a scientific model and we figure out this here in order to understand.

8.3.3 Flaws and Evidence-Based New Modifications: Perspective of Designers

There were some minor modifications to Units 2 and 3, involving the students in more metacognitive activities regarding the nature and use of models. A major change was that the WG decided to provide students with a short text about the nature and aims of models in order to help them deepen and clarify their understandings.

8.4 Identification of Flaws and Induced Modifications Related to Procedural Domain

8.4.1 Objectives

The development of skills relating to design and experimental investigation was added.

8.4.2 Problems and Difficulties: Student' Understandings and Teachers' Views

Following the implementation of TLS2, the students were given a problem-solving task and asked to design a procedure to yield answers to it. Interviews carried out with 25 out of 48 randomly selected students indicated that they achieved good skills to some extent in most aspects of experimental design (see Sect. 6.2), for example, in the dimension "separation of variables," eight of the 25 students assessed provided an acceptable reply, while in the dimension "handling of variables," the results showed that 10 of the students gave acceptable replies. Low scores were recorded only in the dimensions of "devices and instruments" and "device settings"; in "device settings," for example, three students provided an acceptable reply while the rest either gave partially correct replies or made no reference to this dimension.

8.4.3 Flaws and Evidence-Based New Modifications: Perspective of Designers

The WG evaluated the above evidence as supporting the modifications carried out in TLS1. Although results were encouraging, they could and should be further improved. This led to the decision to enhance reflective discussion aiming at fostering understanding of the meaning of investigative procedures, at the expense of some experimental activities. Moreover, students should be further helped to distinguish aspects of experimental design by means of a grid of guiding questions that would focus their attention on the quantities remaining stable or changing during experimentation.

Thus, in Unit 4, instruction was modified to include activities guiding students, for example, when running the thermographic experiment, "which one of the following quantities remained unchanged during the experiment? What quantities have changed?" The same was done with Unit 5, concerning the density experiment. In Unit 6, students were asked to plan an experiment on a stated problem and juxtapose their actions to those executed in a virtual laboratory. Finally, as mentioned in Sect. 8.5, Units 4, 5, and 6 in TLS3 were supplemented by extended homework activities in which students were asked to reflect on the steps of experimentation.

8.5 Identification of Flaws and Induced Modifications Related to the Technological Applications Domain

There were no modifications in this domain.

8.6 Identification of Flaws and Induced Modifications Related to the Relevance and Practicality of TLS2

Teachers were given the guide, went though the activities, and were informed in extensive discussions about all aspects of the TLS. It is notable that both teachers applied almost all the sequence of activities creatively.

Briefly, the WG followed the same procedure for evaluating the relevance and practicality of the TLS2. Comments by students and by the two teachers supported the improved relevance and practicality of TLS2 but pointed also to the need to further reduce the length of the WS and increase the time for discussion, which the WG implemented. In addition, some extended home-based activities were added to enrich the students' in-depth study of conductivity.

9 Results from the Implementation of TLS3

9.1 Results Concerning the Conceptual Domain

The findings of the students' assessment before and after the implementation of TLS3 are presented in Table 7. It is evident that there was noticeable improvement in students' understandings; the pre-test results were similar to TLS2, but there was considerable progress in post-tests and higher achievements than TLS2 in all but one issue, namely, that of the thermal equilibrium of bodies and their environment; for example, there were 92 % acceptable explanations in TLS3, against 63 % in TLS2, of the microscopic processes underlying thermal conductivity in different materials. These results are reinforced by the interviews, as the following example indicates:

R (showing microscopic models of ceramics and metals): Can you tell what materials these are?
S: This is ceramic and this is metal – It has electrons.
R: In which of them is heat going to be conducted faster?
S: In the metal.
R: Can you say why?
S: Because these are electrons (showing the small red balls representing the electrons). With the help of electrons…
R: I see…
S: The molecules of the material start vibrating and because of the existence of the electrons, which contribute to the conduction of heat, they vibrate faster and gradually they conduct heat to the parts with lower temperature….

The teacher reported that the students exhibited ease in responding to the simplified tasks included in their revised WS on the effects of temperature differences on the processes taking place in the micro-world and in employing more scientific terminology as a consequence of the above modifications.

9.2 Results Concerning the Epistemological Domain

Regarding students' awareness relating to the nature and purpose of models, it is worth noting here that the assessment yielded two significant findings. The first concerns their awareness of the nature of models. Results showed that 60 % of the

Table 7 Students' conceptual understandings before and after TLS3 ($N=25$)

Issues	Pre	Post	Examples of types of detected ideas
Thermal equilibrium of bodies and their environment	8 % acceptable answers	52 % correct answer with scientifically acceptable explanations	**Scientific**: *The bodies will have the same temperature as each other and as the house environment.*
		48 % incorrect answers or alternative explanations	**Alternative**: *The temperature of the body will depend on its material.*
Microscopic explanation of *TheCo* through matter	8 % acceptable answers	92 % acceptable interpretations of the phenomenon	**Scientific**: *The vibrating molecules of the food transfer their energy to the molecules of the spoon. As a result these start vibrating transferring energy to the adjacent molecules.*
		8 % alternative explanations	**Alternative**: *The molecules become hot and then the adjacent molecules become hot too.*
The microscopic process of *TheCo* in different categories of materials	36 % acceptable answers	92 % acceptable answer	**Scientific**: e.g., *TheCo through metals is the result of the movement of the electrons.*
		8 % alternative explanations	**Alternative**: *e.g., metal absorbs cold.*
Ranking materials depending on their *TheCo*	10 % scientifically acceptable answers	88 % correct ranking and accepted explanations. The rest incorrect ranking and alternative explanations	**Scientific**: e.g., *metal conducts heat faster than wood.*
			Alternative: e.g., *the explanations are not backed by logic.*
The role of the environment in the insulation procedures	28 % acceptable answers	52 % acceptable answer	**Scientific**: e.g., *the reduction of the temperature of the thermos's content as the result of the heat loss from the insulated walls of the thermos*
		48 % alternative explanations	**Alternative**: *the temperature of the content will have not changed at all due to the insulating material that the walls of the thermos are made of.*
Understanding of factors that make some materials more conductive than others	No pre-test	92 % acceptable answer	**Scientific**: *Material B will conduct heat faster due to the existence of free electrons.*
		8 % alternative explanations	**Alternative**: *the electrons are good heat conductors.*

students considered that the model is "a way to understand a phenomenon and not a replica of a phenomenon," while in pre-test, only 20 % of them held this idea. Also, 20 % of them acquired ideas revealing that "models represent an idea, a theory or the imagination of a scientist," whereas before instruction, the proportion was only 12 %.

The second finding concerns students' ideas about the purpose of models. The results showed that after instruction, the majority of students (68 %) recognized the explanatory use of models, against 36 % before instruction. Moreover, 32 % of them held ideas relating not only to the explanatory but also to the predictive use of models, whereas before instruction, only 20 % recognized the contribution of models to the development of new theories. These results are reinforced by students' answers in the interviews.

R: If we had a powerful microscope, would we see that molecules are blue or perhaps grey as here (shows Fig. 1 and a similar black and white Figure)

S: Neither… hm, they symbolize (molecules), as we said, as we think they are, not as they are.

R: Good! How do scientific models help us? How did the model help you?

S: Well, to interpret phenomena better, to understand what we are studying without doing experiments or being in contact with phenomena.

R: Did the models we used help you?

S: Eh, yes… we could not have seen what happens within the particles of matter if we did a simple experiment… now I understand how heat is conducted with electrons and vibrations.

9.3 Results Concerning the Procedural Domain

The results of the students' assessments after the implementation of TLS3 showed improvement compared to those following the implementation of TLS2 in most of the dimensions that were used as a basis for assessing the students' skills. Some representative results are as follows: for the dimension "separation of variables," while eight of the 25 students assessed provided acceptable answers after the implementation of TLS2, after TLS3, this number increased to 23; for the dimension "handling of variables," 10 students gave acceptable answers after TLS2, whereas after TLS3, the number increased to 20; and for the dimension "device settings," three students provided a fully correct answer after TLS2 and 7 after TLS3.

10 Summary of Modifications

In this section, we present, in Fig. 3, an illustration of the main modifications carried out following implementation of TLS1 and TLS2, respectively.

The units and their titles in each TLS are represented in separate boxes in the eight columns. Units arrayed in the same row belong to TLS1, TLS2, and TLS3, respectively, and represent the structure of each TLS. At the bottom right side, there is a code showing the three types of modifications that were carried out at unit level. Thus, a coding with grid lines denotes new units such as Unit 7 in TLS2; another coding with horizontal lines denotes new units developed out of existing ones, such as Unit 2 in TLS2; and a coding with pale grey indicates abandoned units, such as Unit 5 in TLS1.

It worth noting that modifications between TLS1 and TLS2 involved changes including the abandonment of units, the development of new ones, or the rearrangement of content, indicating radical restructuring at a systemic level. Modifications between TLS2 and TLS3 took place only within units, suggesting a stabilization of structure and refinement of existing units at a local unit level instead of radical restructuring.

11 Discussion and Conclusions

The development of the present TLS refers to a specific didactical problem and has a locally contextualized character, as does any work based on design research in education. Yet the challenge for such studies is to meet the dual goals of refining locally valued innovative interventions and developing more generally usable knowledge (Bannan-Ritkand and Baek 2008; Cobb et al. 2003; Andersson and Bach 2005). Thus, the results and suggestions are discussed from several perspectives.

MER as a design frame was a valuable source for developing the core content but did not suggest much in the way of specific grounds for selecting instructional approach or enlarging the aims of teaching beyond conceptual knowledge. The WG drew on a "domain-specific theory" frame for the role of teachers and context. Practicality and relevance were design principles, but TLS studies in science education fall short of discussing criteria for them even though such works are normally enacted in naturalistic settings. Thus, the WG drew valuable suggestions from DBR studies for elaborating criteria with regard to viability (Kelly et al. 2008a, 2008b). Overall, the design of the TLS took advantages of suggestions from TLS and DBR studies. In the context of the discussion for the role and applicability of different suggested design frames in TLS literature (Psillos and Kariotoglou), we consider that the creative and adaptable utilization of several frames rather than one may bear fruit and inspire innovative solutions to didactical problems as in our case (Hjalmarson and Lesh 2008).

Contextual-educational constraints influenced the decision to develop the TLS as complementary to the main curriculum in order to provide for the in-depth study of conductivity, to afford students with reasonable didactical time to immerse into inquiry and add to the viability of this innovation. To implement such an innovative TLS requires intensive immersion into its complexities and empirical refinement of the enacted intervention. Therefore, the members of WG opted for a progressive evolution of the TLS of limited scope in the initial phase and with gradual enrichment of goals and activities in subsequent phases (Sandoval and Bell 2004). Thus, TLS1 did not focus on procedural and epistemological knowledge. Usually, in TLS studies, researchers implement initial versions which more or less include the suggested overall content and aims and wait for feedback from empirical data. In the present study, the stepwise strategy that was followed helped both researchers and teachers gain deep insights into the flaws of TLS1, since they handled the familiar domain of conceptual knowledge supplemented by technological applications. Based on the evidence from the first implementation, the WG found that while TLS1 was reasonable, effective and implementable to the classroom, certain modifications were necessary.

Iterative development involves successive approximations of a desirable intervention, helps sharpen aims and deepen contextual insights, and contributes to the drafting of design principles (Kelly et al. 2008a, 2008b). The WG's decision to apply a domain-oriented model to iteration provided a functional approach to offering guidelines for design and reflection that targeted the closure of one or more gaps between the intended, implemented, and attained TLS. We argue here that such a domain-oriented model differs from simply considering the nature of learning objectives set for units or activities. The conceptual, epistemological, procedural, and technological domains were organizing principles running all through the TLS, functioning as heuristic tools for proceeding to iterative approximations and reflective presentation of enacted design involving complex interactions in naturalistic settings (Cobb et al. 2003). We suggest that the domain-oriented model facilitated comprehensive linking of evidence, decisions based on evidence, and design factors with modifications.

At a more general level, we subscribe to the perspectives of developing domain- or topic-oriented theories of teaching and learning science proposed by several researchers (e.g., Andersson and Bach 2005). We consider that teaching and learning science may be improved by describing obstacles and explaining contextualized local solutions to applying innovations under given constraints. Elaborating design principles or models may help further this aim. We consider that the present work contributes broadly to the iterative development of a TLS in science at a more general level by suggesting a specific model called DOIES, which is presented in Fig. 4 below.

DOIES stands for Domain-Oriented Iterative Evolution of a Sequence. In the present case study, it concerns the implementation of an inquiry-based complex scientific content in a traditional educational environment not accustomed to innovations. The main element of the model is the limited scope of the initial TLS based on selection of the prevailing domain in the targeted classrooms. This stepwise proposal is innovative with regard to TLS literature. In traditional classrooms, for example, in Greece, the prevailing domain is normally conceptual, but other domains may be chosen in a different context. This is illustrated in Fig. 4 by the strong grey color of conceptual and technological domain and the lighter color of the procedural and epistemological ones in the bottom line visualizing TLS1. The second main element of the model is the domain orientation of iterative improvement which links the design, implementation, and evaluation of the innovative intervention. The arrow on the left illustrates the gradual development of the integrative

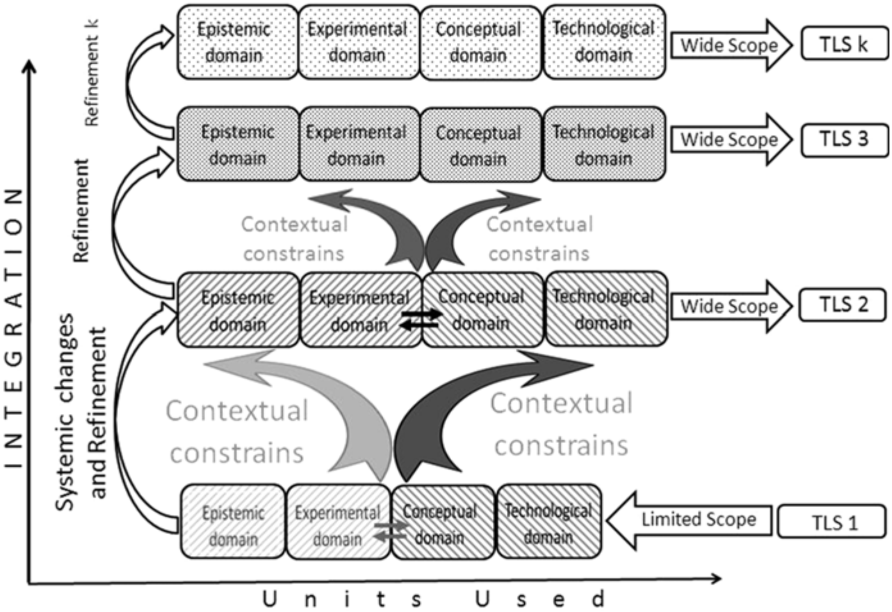

Fig. 4 A Model for a Domain Oriented Iterative Evolution of a TLS

approach to inquiry, including the enacted procedural and epistemological domains in a second phase. Following in-depth insights from the first trial, all domains may be fully or partially enriched and embedded in a TLS at study. This is illustrated by the strong grey color of all boxes in the second line of Fig. 4, visualizing TLS2. Subsequently, the expected modifications will have an "exponential" rather than a linear character, leading to local rather than systemic modifications tending towards fitting intended, implemented, and attained goals. This is illustrated by the upper line visualizing hypothetical TLSk, which may take place after the third or *k*th trial, implying that there may be changes at any trial, yet there will be some stabilization of the TLS and refinements are expected to become minor depending on specific contextual variations in classrooms.

Concerning evaluation, several TLS studies focus mainly on student' conceptual understanding (e.g., Besson et al. 2010). In the present TLS, the WG set an integrated approach to inquiry as one a priori design principle; therefore, evaluation was based on multiple sources of students' understandings. Evaluation was also based on capturing teaching as well as learning, by investigating teachers' views and analyzing materials. Evaluation of data from the implementation of TLS1 revealed flaws begging for modifications; these have been discussed in detail.

Concerning teachers' suggestions, one notable difference compared to researchers was that the former were looking for appropriate modifications and the latter for evidence-based ones (Leach 2007). Teachers' comments on running the TLS and classrooms interactions were based on their professional knowledge and involved creative insights and knowledge about "what works" and what the conditions for a "good" science lesson should look like. Overall, these proved to be valuable to the WG in supporting or even reconsidering students' learning outcomes. However, it is notable that teachers' professional knowledge was not extrapolated to unknown themes. In the design phases of TLS1, they analyzed the activities and agreed to include composite materials and density, of which they had no teaching experience. They changed their views following the implementation of TLS1 concerning students' difficulties in these themes. This might indicate an in-depth yet rather limited perspective of teachers' professional knowledge, an issue which needs further research.

There was a "grain size" difference between the teachers' and researchers' suggestions; the first was confined to improving the existing structure of the TLS, while the second had a global perspective. For example, teachers noticed that students were overloaded with activities in TLS1 and, to some extent, in TLS2, but it was the researchers who, inspired by knowledge of didactics, introduced reflective discussions all through the TLS, including a whole new unit. Similarly, the introduction of experimental design and epistemological activities related to models in TLS2 was feasible given the viability of TLS1 and was related to suggestions from didactics (Johnstone and Al-Shuaili 2001). In sum, decisions concerning iterative modifications were differentially affected by design and contextual factors, as discussed in Sect. 3.1; multiple classroom evidence, as discussed in Tables 4 and 5 and Sects. 7 and 8; and theoretical perspectives in didactics of science, as discussed above and in Sects. 7 and 8 concerning the perspective of designers.

Modifications were classified as local and systemic. Systemic changes involved abandoning an entire unit (Unit 6) and implementing Units 7 and 8 or restructuring Units 2 and 3. Local modifications were effected within units, e.g., insertion of a new exemplary demonstration experiment (the drop of wax) in Unit 3. From Fig. 3, it appears that the nature of the modifications changed considerably between TLS2 and TLS3, from systemic reorganization to local refinement of various elements. We consider this somewhat "exponential pattern" as indicating a closing of the gap between conceived and working structure and activities and stabilization of a TLS adaptable to both students and teachers.

We notice, though, that a number of core features of the TLS remained stable, including the macro/micro treatment of conductivity, the choice and exploratory use of models, the relation of models to experiments, the qualitative study of factors affecting heat conduction, scaffolding students from structural to open investigations, the use of ceramics and metals as showcases, and the position of technological applications. A possible interpretation is that the design, choice, and, to some extent, the organization of core elements of TLS1 were based on suggestion from MER and "domain-specific theory frame" adapted to expected classroom context taking into account teachers and students' practices and the affordance of "flexible zone" stipulated by the Greek curriculum.

The effectiveness of the modifications performed is supported by the improvement in students' understandings over various editions of the TLS, the quality of teachers' comments, and the nature of the modifications. There was a considerable improvement in all conceptual issues between TLS1 and TLS3, as is clear from Tables 4 and 7, for example, although there were no initial differences between participating students in the different classes, their conceptual understanding improved remarkably between TLS1 and TLS3 in the difficult issue of the microscopic explanation of heat conduction. However, comprehending the thermal equilibrium of bodies and their environment remained difficult for them, despite the progress made between TLS1 and TLS3. Regarding students' awareness of models, there were no data from TLS1. The results from TLS3 show that the majority of students achieved considerable progress concerning the nature of models before and after TLS3, since they recognized the explanatory use of models and some of them became aware of their predictive function. There was also progress between TLS2 and TLS3 concerning students' achievements in experimental design.

12 Suggestions for Research and Development

The literature shows that there is a scarcity of evidence-based approaches focusing (partly or wholly) on thermal conductivity as part of introductory materials science aiming at helping students at secondary level achieve solid understanding of macroscopic properties, underlying processes, and technological applications. It is legitimate to propose the use of TLS3 in the context of the curriculum "flexible zone" as a product for wider use by other teachers on the grounds that there is evidence that it "works" and is viable within the context of the local educational and administrative environment. This does not mean that it is the best way, but that it is a well-documented product.

In the context of TLS studies, there has recently been a discussion on the nature and dissemination of the TLS, whether such sequences should consist of a structured set or be loosely structured, with a core and suggestions for activities. We consider that for traditional teachers accustomed to a fixed curriculum, the first option falls into their "zone of proximal development" in the Vygotskean sense. The TLS3 materials can inspire creative use on the part of teachers, since the design principles are set out clearly and enacted through the well-documented and structured set of activities. TLS3 also provides insight into how lower secondary students may be introduced to inquiry teaching in the context of a traditional environment. The WG considers that teachers may not follow all the suggested activities but may be motivated to use them or reflect on their use and their existing practices.

Finally, and obviously, we suggest the DOIES model could be applicable beyond the present case study, since it includes specific suggestions for the iterative development of a TLS involving complex content and instruction.

Appendix: Sample of Evaluation Tasks

Conceptual Questionnaire

- During winter you visit your country house in the mountains. The *temperature* inside the house is 6°C. There are different items left in the house. Can you predict what the temperature of the following items will be?

  A. (a) A woollen sweater ___°C
     (b) A metal saucepan ___°C
     (c) A wooden table ___°C

  B. Why do you think these items will have the specific temperature?

- A friend of yours stirs the food with a *metal spoon* while cooking. After a while he starts feeling his fingers burning. Why do you think this happens?
- Can you explain what happens to the microscopic particles of matter which the metal spoon is made of?

Experimental Questionnaire

Kate has two heat resistant mugs, “A” and “B”. The mugs are similar, except that they are made of different materials. Kate claims that if we put the mugs on a heater, the water in mug “A” warms up faster that the water in mug “B”.

How will you find out if she is right?
Can you set up an experiment to check her statement?
What will you need?
What will you observe?

Modelling Questionnaire

What do you think that a scientific model represents? Justify your answer and give two examples.
What do you think is the purpose of a scientific model? For what can the model be used?

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Design, Development and Refinement of a Teaching-Learning Sequence on the Electromagnetic Properties of Materials

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1 Introduction

This study departs from the premise that teaching science as inquiry provides a powerful approach that allows coupling the teaching elaboration of concepts with epistemic discourse intended to help students appreciate core ideas relevant to the *nature of science* (NOS) (NRC 1996; AAAS 1993). We report on a research effort targeted at the development of a teaching-learning sequence (TLS), drawing on this instructional approach. The teaching-learning sequence is situated in the domain of materials science. It is specifically focused on the *electromagnetic properties of materials* (EPM), and it seeks to promote the dual objectives of helping students (1) develop conceptual understanding needed for analyzing certain phenomena involving magnetic interactions and (2) recognize the role of science and technology in society and appreciate their distinction and their relationship (Constantinou et al. 2010), which constitutes an important component of the overall goal to promote understanding about NOS (McComas 1998; Osborne et al. 2003).

The study draws on the paradigm of design-based research (Brown 1992; Collins 1992; Edelson 2002). It reports on the process of refining the teaching-learning sequence, on the basis of accumulated research evidence collected through its implementation in authentic learning environments. In particular, we seek to illustrate how the empirical data collected during the implementations could serve to guide the process of refining the activity sequence so as to promote its targeted learning objectives more effectively. We report on particular instances in which the data on student learning outcomes have led us to identify specific limitations of the teaching-learning sequence in terms of its facility to promote certain learning

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objectives. We elaborate on the revisions that we have undertaken so as to address the identified limitations and also on how we have drawn on empirical data from subsequent implementations of the revised version of the teaching-learning sequence to derive indications as to the added value brought about by these revisions. Our main objective is to provide an account of the variation in both the range of limitations that could be identified and also the possible revisions that could be undertaken. Also, we seek to demonstrate how empirical research could serve to provide insights into the utility of the revisions. In particular, we seek to address the following issues:

1. What is the nature of the limitations that were identified during the implementation of the EPM teaching-learning sequence?
2. What is the nature of the various revisions that have been undertaken in refining the EPM teaching-learning sequence?
3. How could empirical evidence on students' learning outcomes serve to both reveal possible limitations of a teaching-learning sequence and also evaluate the potential effectiveness of the corresponding revisions?

Despite the rather narrow focus of this case study, we anticipate that the findings presented could lead to wider implications that could be generalized beyond the scope of the case study.

The chapter is organized in five sections. The first includes an overview of key ideas that form the backdrop against this study. The second offers an account of the structure and content of the teaching-learning sequence that has been developed. The third section provides information about the research methods employed in this case study. The fourth section presents the findings that have emerged, whereas the last section provides a discussion of the ensuing implications.

2 Literature Review

2.1 Learning in Science: A Holistic Perspective

The consensus point reported in the science education research literature is that learning in science constitutes a multifaceted construct that extends beyond mere content knowledge (Duschl et al. 2007). Two other components that are widely recognized as important elements of learning in science include (a) understanding of fundamental aspects of NOS and (b) the ability to apply valid reasoning strategies while processing data. The first is needed for helping students develop an informed view about how science operates and how scientific knowledge is produced, organized, and justified (Lederman 2007). The second is needed for enabling students to competently process data and draw valid evidence-based inferences (Duschl et al. 2007). This perspective of science learning as a multifaceted structure seems to be in conflict with conventional science teaching practice, which tends to exclusively focus on content knowledge largely ignoring the remaining components. Any attempt to develop teaching-learning sequences should take into account this multifaceted nature of learning in science and explicitly seek to address its various constituent components in an integrated manner.

2.2 Teaching Science as Inquiry

There are increasing calls for *inquiry* as a context for science teaching and learning (NRC 1996; AAAS 1993). Inquiry is an overarching term encompassing a wide range of processes, including making observations, formulating investigable questions, designing and conducting experiments, analyzing and interpreting data, formulating evidence-based explanations, and constructing and critiquing arguments (Duschl et al. 2007; Grandy and Duschl 2007; NRC 1996). Accordingly, teaching science as inquiry entails learning environments organized so as to engage students in these processes in a systematic and coherent manner with some degree of controlled authenticity. This teaching approach is deemed likely to promote coherent conceptual understanding, enhance authenticity in classroom practices, and facilitate students' exposure to the epistemic underpinnings of science and scientific inquiry. An added advantage of this approach is that it offers a powerful learning environment that allows integrating different classes of learning objectives, thereby facilitating holistic science learning. That is, it acquaints students with a learning environment within which they can acquire experiences with phenomena of interest, make systematic observations about their operation, develop and elaborate conceptual models for the interpretation and prediction of their behavior, and also engage in explicit, reflective discourse about the epistemic aspects of these processes (Khishfe and Abd-El-Khalick 2002).

Despite the wide recognition of its potential, teaching science as inquiry is rare in schools and the mainstream science curricula (European Commission 2007). One possible reason for this relates to the lack of existing capacity, mechanisms, and structures for guiding teachers on how to engage children in inquiry-based practices. Another reason, directly related to this study, is associated with the scarcity of inquiry-oriented curriculum materials that could effectively support this shift.

2.3 Distinction and Connections Between Science and Technology

For a very long time, until the Renaissance, technological development relied entirely on the crafts. Until that time, major technological developments were brought about by craft technologies without the slightest contribution from science. A series of advancements achieved in the last few centuries have greatly changed this state. Technology has ceased to advance only as a result of accumulated practical knowledge and empirical observations of factual correlations often emerging through trial and error processes. Over these last few centuries, the idea of developing models and theories in order to establish a pattern of continuous technological growth that relies on purposeful innovation has taken hold. This has established a rather complex relationship between science and technology.

Despite their strong connection, it is the case that science and technology constitute two distinct domains of human activity that serve entirely different social purposes. Science aims at producing reliable knowledge about how systems function; technology seeks to generate solutions to problems encountered by society or to develop procedures or products that meet human needs (AAAS 1993; Agassi 1980; Arageorgis and Baltas 1989; Constantinou et al. 2010; Custer 1995; Gardner 1993, 1994; International Technology Education Association 2000; NRC 1996). An additional distinction that could be drawn between these two fields relates to the core process they rely on. Specifically, design is the core process in technology (International Technology Education Association 2000), whereas investigation is a core process in science (Lewis 2006).

Despite being distinguishable on the basis of their main goal and the core processes they rely on, science and technology are strongly interconnected. Their connection could best be described as a bi-directional relation, in that each field is both informed by and informs the other. For instance, the technological equipment used in laboratories enables experimental activities and, hence, sustains the interaction between theory and experiment, which is an integral component of science as a research field. This clearly depicts how research in science relies on technology. On the other hand, it is the case that the development of this same technological equipment would not have been possible without the insights provided by corresponding advancements in science. This, in essence, depicts how technology relies on science.

Distinguishing between science and technology is recognized as an important aspect of the nature of science (NOS) and, hence, a significant learning objective of science teaching (McComas 1998; Osborne et al. 2003). In addition to being an important and desired learning outcome of science teaching on its own right, promoting this distinction could also bring about additional benefits. For instance, it could serve to enhance students' interest towards science and technology courses (Gago et al. 2004; NSF 2003; OECD 2006). Also, it could support students in making more informed, and presumably more successful, decisions about future careers.

2.4 Materials Science as an Instructional Context

Materials science, as a research field, facilitates the link between science and technology. It is in this branch of science that we now develop standards and instruments for measuring an increasingly diverse set of properties, the combinations of which have become progressively more important to the market place. In addition, it is also in this branch of science that special materials are designed for customized applications through chemical synthesis and various forms of treatment. The selection to situate the teaching-learning sequence in this particular domain seems productive and fruitful for a number of reasons. First, despite the increasing technological applications of materials science and, correspondingly, their increased social relevance, there is little attention devoted to this topic in school science. An additional reason relates to the potential of this instructional context to support the explicit objective of the teaching-learning sequence to help students appreciate not only the distinction but also the connections between science and technology. One way of promoting this objective involves engaging students with teaching-learning sequences designed for bridging between scientific inquiry and technological design (Lewis 2006). Materials science offers a productive context for implementing this bridging.

3 Overview of the Teaching-Learning Sequence on Electromagnetic Properties of Materials (EPM)

3.1 Context of the Design of the Teaching-Learning Sequence

One of the main reasons for the dominance of the content delivery teaching model in school science relates to the various constraints that impede attempts to introduce and scale up teaching innovations. One possible way to contribute towards addressing this problem entails the adoption of a new paradigm for developing such innovations. One potentially useful paradigm involves the organization of school-university partnerships. Establishing multidisciplinary teams could be useful for the development (and classroom-based evaluation) of effective research-based teaching-learning sequences. This paradigm relies on participative processes, which draw on multiple sets of complementary expertise (e.g., researchers and teachers). In such synergies, researchers are expected to contribute their academic and research expertise, whereas teachers are expected to contribute their pedagogical expertise. Together, this group is likely to produce sustainable innovations that could be more likely to have a real influence on classroom learning. In this study, we explicitly sought to draw on this particular paradigm. For this purpose, we organized a working group, consisting of five researchers from the field of science education and four experienced physics teachers. This working group was active throughout this case study. Its members worked closely together and assumed, at the collective level, the responsibility for designing and refining the teaching-learning sequence.

3.2 Learning Objectives

The teaching-learning sequence seeks to promote two main learning objectives. The first involves students' conceptual understanding of fundamental ideas relevant to magnetic interactions and electromagnetic phenomena, including (1) the interaction between magnets and other objects, (2) the magnetic field as a model for explaining relevant observations (e.g., how the strength of the interaction changes as a function of distance), (3) the magnetic domains model and the process of magnetization, and (4) factors influencing the operation of an electromagnet.

The second objective relates to the enhancement of students' epistemological awareness about NOS with the focus being placed on their understanding of the distinction and the interrelations between science and technology. In particular, the teaching-learning sequence sets out to help students (a) appreciate that science and technology are two distinct albeit strongly interconnected fields, (b) appreciate certain interactions between the two fields, and (c) distinguish between these two fields in terms of the goal they seek to pursue (enhancement of understanding of how nature operates versus development of a solution to a given problem) and also in terms of the core processes they draw upon (investigation versus design).

3.3 Overview of the Structure and Content of the Teaching-Learning Sequence

The teaching-learning sequence consists of six units, organized in two main parts. The first part (Units 1–4) comprises a sequence of inquiry-based activities intended to guide students to gradually develop and elaborate conceptual models for analyzing (qualitatively) the operation of increasingly more complicated physical systems involving electromagnetic properties of materials. At the same time, the activity sequence seeks to support students to overcome well-documented conceptual or other difficulties they tend to encounter (Chabay and Sherwood 2006; Tanel and Erol 2008). This first part of the teaching-learning sequence has extensively relied on *Physics by Inquiry* (McDermott and The Physics Education Group at the University of Washington 1996). The second part (Units 5–6) engages students in a design project embedded in a specific problem-solving scenario. This involves the design and development of a model of a magnetically levitated train that incorporates three specific features, namely, suspension, propulsion, and magnetic shielding.

These two parts of the teaching-learning sequence are closely connected in the sense that the process of designing the train is expected to be largely informed by the concepts and ideas introduced and elaborated in the first part of the teaching-learning sequence. For this reason, the technological problem to be solved in the second part was introduced from the outset so as to make it more likely for students to be attentive to information that could possibly be useful in designing the train and satisfying the corresponding specifications. Additionally, it was assumed that the early introduction of the technological project could contribute towards enhancing and sustaining students' interest.

Table 1 provides an overview of what is involved in each of the six units. A more elaborate description is available in the guide for teachers that accompanies the teaching-learning sequence (Constantinou and The Learning in Science Group at the University of Cyprus 2009).

Table 1 Overview of the units included in the teaching-learning sequence

Unit 1	It seeks to elaborate fundamental ideas related to magnetism while also addressing well-documented student difficulties. (e.g., tendency to conceive of the strength of a magnet as being determined by its size).
	It guides students to:
	explore the interaction of magnets with other magnets, ferromagnetic, diamagnetic, paramagnetic, and other materials.
	identify the poles in magnets of various shapes.
	appreciate the earth as a magnet and distinguish between geographic and magnetic poles.
Unit 2	It addresses the concept of the magnetic field and its facility to account for interactions at a distance. It guides students to develop a representational model of the magnetic field for magnets of different shape and test its applicability in various situations.
Unit 3	It engages students in a set of activities involving instances of magnetization and demagnetization and guides them to make certain observations and develop the model of magnetic domains as a means to (a) account for those observations and (b) make predictions about the behavior of other relevant systems.
Unit 4	It engages students in constructing electromagnets and, subsequently, in designing and carrying out experiments for addressing certain investigable questions about factors that could possibly influence the strength of an electromagnet. This provides a context for elaborating key ideas of electromagnetism, which are expected to be used in the next unit for the design and construction of the model train. Emphasis is placed on the need to ensure experimental designs with appropriate control of variables, so as to increase the likelihood for deriving trustworthy conclusions (Boudreaux et al. 2008).
Unit 5	It involves the design and development of a model of a magnetically levitated train, drawing on the ideas explored in the previous units. Students are guided to employ a technological design approach that encompasses a range of processes, including (a) need analysis, (b) problem formulation, (c) collection of ideas, (d) elaboration and articulation of specifications, (e) technical drawing, (f) selection of materials and apparatus, (g) construction of a solution to the problem of interest (i.e., development of a train model that exhibits the features of levitation and propulsion and offers magnetic shielding inside the wagon), (h) evaluation and refinement of the solution.
	These processes should not be interpreted as stages implemented in a linear, stepwise manner. Rather, students are encouraged to move back and forth through these key processes, as needed, with the purpose to arrive at the optimum solution to the technological problem of interest. Also, emphasis is placed on systematically engaging students in explicit epistemic discourse about the connections and distinction between science and technology.
Unit 6	It engages students in the process of evaluating their train models. Also it presents them with additional reflective probes intended to help them further clarify and articulate the bi-directional relationship between science and technology.

4 Research Methods: Enactment, Evaluation and Refinement of the Teaching-Learning Sequence

4.1 Context of the Enactments

The teaching-learning sequence has been enacted in classroom settings, with the aim to explore its potential to promote the specified learning objectives and to collect evidence that could be used to identify possible improvements. During each enactment, we collected and analyzed empirical data on students' learning outcomes. The time needed for the implementation of the teaching-learning sequence, including the data collection process, was about 20 ninety-minute sessions. After each enactment, the activity sequence underwent refinements, on the basis of the available empirical data. The teaching-learning sequence was exposed to a total of six implementation-evaluation-refinement cycles, which involved a total of 294 participants. Two of the enactments took place in the context of a physics summer school organized and coordinated at the University of Cyprus. Two of the remaining implementations occurred in a science content course for prospective elementary teachers studying at the Department of Education at the University of Cyprus. Finally, the last two enactments took place in school classroom environments. In all cases, the implementation took place in intact classes. Table 2 summarizes the context for each of these implementations. In each case, the implementations were undertaken by the physics teachers who participated in the working group. Prior to and during each implementation, the working group had regular preparatory meetings so as to discuss and agree on issues associated with specific activities and also to discuss particular learning difficulties that were encountered by students and possible ways to address them.

One point that has to be noted refers to the variation in the instructional context across these six implementations, in terms of the characteristics of the student population. In two of the enactments, participants were prospective teachers, whereas participants in the remaining four enactments were highschool students. In addition, two of these latter enactments took place in regular school classes, whereas the other two were situated in a physics summer school. This variation can be thought of as a limitation to the study; in certain cases, the revised version of the teaching-learning sequence was tested with a different student population than the one that actually led to those revisions. We believe that as a result of the variety in the educational con-

Table 2 Information about the context of the implementations of the teaching-learning sequence

Enactment	Year	Instructional context	Participants
1	2008	Physics summer school	16 Students aged 15–17
2	2008	Undergraduate science content course	61 Pre-service teachers
3	2009	Undergraduate science content course	71 Pre-service teachers
4	2009	Three high school classes	72 Students aged 15–16
5	2009	Physics summer school	30 Students aged 15–17
6	2009	Two intact high school classes	44 Students aged 15–16

texts, the teaching-learning sequence is more robust and can be used by a wider range of teaching staff in a variety of contexts. The data that we have collected do offer valuable insights into the potential effectiveness of the revisions that were undertaken in each case and provide indications about the gradual convergence of the teaching-learning sequence to an increasingly more stable ad more effective version.

4.2 Data Sources

During each enactment, we collected data on students' learning outcomes using a number of sources. Specifically, we used a series of open-ended tasks to assess students' understanding of specific concepts and ideas relevant to magnetism and electromagnetism. In these tasks, students were asked to analyze (e.g., predict, or account for, the behavior of) specific physical systems through applying ideas about magnetism and electromagnetism addressed in the teaching-learning sequence. Students responded in writing, while a sub-sample of them also participated in follow-up interviews, intended to provide further insights into their reasoning. Students' appreciation of the distinction between science and technology was assessed through an instrument that had been developed in another study (Constantinou et al. 2010). This instrument consists of a number of multiple-choice items and an open-ended item. An additional main data source included the products created by students in the context of the technological project. These include the actual train model constructed by the students and the accompanying posters portraying the key features of the train models. Finally, two additional data sources that served a supplementary role include the worksheets completed by the students while working through the teaching-learning sequence and the reflective journals kept by the teachers during the implementations. It is important to note that not all data sources were used in every enactment, even though this was indeed the case in most of them. However, each source was used in at least one of the enactments.

4.3 Data Analysis

Students' responses to the open-ended assessment tasks were exposed to content analysis (Krippendorff 2004) so as to organize them into a limited set of categories that describe the qualitatively different ways of reasoning about the tasks. The categories were not imposed a priori. Instead, the categorization scheme emerged gradually during data analysis, and it underwent several revisions at various stages throughout this process before converging to its final version.

The posters and the train models constructed by students in the second part of the teaching-learning sequence were exposed to artefact analysis (Kellogg 1990). This was focused on the extent to which the models constructed by groups of students satisfied the three main specifications that had been formulated (i.e., levitation, propulsion, and shielding). Specifically, we inspected the train models constructed by the students, and we consulted the accompanying posters so as to document whether (but also how) each of the three features was addressed. This provided us with useful information about the extent to which students engaged with this technological project in a thorough and thoughtful manner. Also it yielded valuable insights into students' ability to transfer concepts dealt with throughout the activity sequence to the specific problem at hand. For instance, it allowed us to evaluate students' ability to apply the concept of polarity and the effect of the number of coil turns on the strength of the electromagnet so as to achieve the propulsion of the train; propulsion can be achieved by arranging the electromagnets in such a way that the polarity alternates and the distance between consecutive electromagnets is kept constant.

5 Findings

In this section, we elaborate on how we have used the various implementations of the teaching-learning sequence as a context for evaluation and gradual improvement. Specifically, we describe how we drew on the empirical data on students' learning outcomes as a means to identify parts of the teaching-learning sequence that did not function effectively and how this guided its refinement process so as to address those limitations. The section is divided into four parts, each elaborating on a specific type of limitation that we have identified. The first type of limitation concerns the facility of the teaching-learning sequence to help students develop coherent conceptual understanding about particular key ideas. The second refers to the extent to which the teaching-learning sequence provided students with sufficient support to transfer and apply key concepts to the process of designing and constructing the train model. The third type of limitation refers to the extent to which students' interaction with the teaching-learning sequence enabled them to productively engage with the technological project involving the design and construction of the train model. Finally, the fourth type of limitation pertains to the facility of the teaching-learning sequence to help students emerge with informed and epistemologically coherent insights into the distinction and the interrelationships between science and technology.

A key criterion that we employed in selecting the limitations to focus on was the breadth of coverage in terms of the learning objectives targeted at by the teaching-learning sequence. Thus, we have sought to include examples of limitations that pertain to all the main learning objectives. Another important criterion we sought to satisfy relates to the breadth of coverage of the range of possible limitations that could be encountered and the possible revisions for addressing them. We have aimed to broaden coverage so as to convey a sense for the substantial underlying variation, in this respect.

Each of the four parts included in these subsections (a) provides an overview of the limitation in each case and the data that led to its identification; (b) describes the revisions that we have undertaken so as to address that limitation; and, finally, (c) provides data from subsequent implementations of the revised teaching-learning sequence so as to provide indications as to the added value brought about by these revisions. In addition to illustrating the impact of the revisions, the evidence that we report in each section is also intended to serve an additional purpose, namely, that of revealing what could be achieved by students through their engagement with the teaching-learning sequence.

5.1 Limitation I: Lack of Facility to Promote Conceptual Understanding about Certain Ideas

The first type of limitation that we identified concerns the facility of the teaching-learning sequence to help students develop particular concepts and models associated with the analysis of the behavior of systems involving magnetic/electromagnetic interactions and overcome specific difficulties they tend to run into. This is illustrated below, through two specific examples.

5.1.1 Understanding the Model of Magnetic Domains

5.1.1.1 Description of the Identified Limitation

The model of magnetic domains helps in accounting for the behavior of magnets as well as the magnetization and demagnetization of ferromagnetic materials. The development of this model was initiated by focusing on the properties of magnetic stacks. Students were asked to create stacks out of small magnets and investigate whether their behavior was similar to that of a single magnet. They also investigated how the strength of the stacks changed as a result of the incorporation of additional magnets in various, random orientations. Next, they moved to a section that dealt with the notion of the magnetic field, and then they revisited magnetic stacks and were introduced to the model of magnetic domains as a means to explain the magnetic behavior for both magnets and ferromagnetic materials. Students evaluated the appropriateness of this model in describing and explaining the behavior of magnetic materials through a series of activities.

Understanding the model of magnetic domains and applying it in accounting for the behavior of relevant systems involving magnetic interactions appeared to be a rather difficult task for students. Figure 1 provides an overview of one of the tasks that we used for assessing students' understanding of this model.

Table 3 presents the results of the categorization of students' responses to this assessment task. The first column summarizes the rationale underlying each of the different categories of response that we have been able to identify, whereas the second column illustrates each category through a typical student response. The last four columns show the frequency and percentage of responses falling in each of the categories. The first two of these columns (third and fourth columns) refer to an implementation with a version of the teaching-learning sequence that contained the initial form of the activities.

The first category contains the responses that could be deemed valid. Students in this category were in a position to correctly apply the magnetic domains model so

A ferromagnetic bar is brought near a magnet. Three compasses are placed around the ferromagnetic bar as shown below. In what direction would the needle in each compass be pointing? Draw the needle in each compass and explain your reasoning

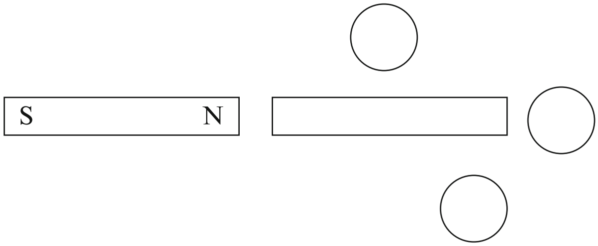


Fig. 1 Overview of task for assessing students' understanding of the magnetic model (McDermott and The Physics Education Group at the University of Washington 1996)

as to account for the magnetization of the ferromagnetic object. Specifically, these students were able to describe the ferromagnetic bar as a collection of magnetic domains and demonstrated appreciation of the idea that the ferromagnetic bar could become magnetized, when these domains are forced to align, relative to each other, under the influence of an external magnetic field. The second category includes the responses of students who also exhibited appreciation of the fact that the ferromagnetic bar becomes magnetized as a result of its proximity to the magnet and also referred to the fact that the orientation of the needles in the three compasses would be determined by the magnetic field of the ferromagnetic bar. However, these students did not refer to the idea of the magnetic domains and, hence, failed to account for the magnetization process. Students in the third category did treat the ferromagnetic bar as a magnet and referred to the interaction between the compasses and the bar. However, they avoided any reference to the magnetization process or the interaction between the magnet and the ferromagnetic bar. Thus, it is not obvious whether they did appreciate that the ferromagnetic bar only becomes magnetized under certain conditions and, hence, whether they differentiated between a ferromagnetic object and a permanent magnet. The fourth category includes the responses of students who stated explicitly, or impliedly, that ferromagnetic materials do not behave like a magnet and, therefore, the ferromagnetic bar would not influence the position of the compass needles. Finally, the last category contains irrelevant responses that failed to address the question at hand.

As shown in Table 3, a significant percentage of students (32 %) seemed to have grasped the essence of the model of magnetic domains and were able to correctly employ it for analyzing the magnetization of the ferromagnetic bar (first category of response). However, this percentage was much lower than what we would have expected. We concluded that there was a need to provide additional activities so as to help students gain experiences in using the model of magnetic domains to analyze relevant phenomena. Next, we describe the revisions that we undertook in our attempt to address this limitation of the teaching-learning sequence.

Table 3 Categorization of students' responses to the task for the assessment of conceptual understanding about the magnetic domains model

	Category of response	Indicative student response	Data from the implementation of an initial version of the TLS		Data from the implementation of a revised version of the TLS	
			Pre-test	Post-test	Pre-test	Post-test
			N (%)	N (%)	N (%)	N (%)
1	The magnetic field lines align the magnetic domains of the ferromagnetic bar and poles appear at its ends. The orientation of the compasses follows the magnetic field lines.	The ferromagnetic bar consists of many small magnets (magnetic domains), which are positioned in random orientations. When the ferromagnetic bar is placed into the magnetic field of a permanent magnet, these small magnets align and the ferromagnetic material acquires magnetic properties (magnetic poles appear at its ends). Thus, the ferromagnetic bar acts as a magnet, and when the compasses are placed near its north pole, they align according to the magnetic field lines of the ferromagnetic bar. So, the south pole of the compasses points towards the north pole of the magnet.	1 (2 %)	18 (32 %)	1 (3 %)	49 (72 %)

(continued)

Table 3 (continued)

	Category of response	Indicative student response	Data from the implementation of an initial version of the TLS		Data from the implementation of a revised version of the TLS	
			Pre-test	Post-test	Pre-test	Post-test
			N (%)	N (%)	N (%)	N (%)
2	The ferromagnetic bar is magnetized and poles appear at its ends. The orientation of the compasses is determined by the magnetic field of the ferromagnetic bar or magnetic interactions between the ferromagnetic bar and the compasses' needles.	The ferromagnetic bar is magnetized when brought close to a magnet and poles appear at its ends. The poles are determined according to the magnet's pole that attracts the ferromagnetic bar. The compasses orient according to the poles of the ferromagnetic bar.	17 (30 %)	18 (32 %)	12 (30 %)	16 (24 %)
3	The ferromagnetic bar acts as a magnet. The orientation of the compasses follows the magnetic field lines or magnetic interactions.	The compass and the ferromagnetic bar act as magnets. Thus, the opposite poles are attracted. Furthermore, the ferromagnetic bar will have its own magnetic field.	21 (38 %)	12 (21 %)	9 (22 %)	-
4	The orientation of the compasses depends on the magnetic field of the magnet. The ferromagnetic bar does not affect the compasses.	The south pole of the compass is positioned towards the north pole of the magnet, because it is affected by the magnetic field of the magnet. Even though there is a ferromagnetic bar placed between the compass and the magnet, the orientation of the compass will not be affected because the ferromagnetic bar is not a magnet.	17 (30 %)	6 (10 %)	18 (45 %)	1 (1 %)
5	Irrelevant responses	Compasses serve to indicate the direction of the north pole of the earth	-	3 (5 %)	-	2 (3 %)

5.1.1.2 Revisions That Had Been Undertaken to Address This Limitation

In revising the activity sequence so as to enhance its potential to help students emerge with functional, coherent understanding of the model of magnetic domains, we decided to alter the order of the activities included in the teaching-learning sequence. Specifically, we changed the position of the activities that deal with this model so that they immediately follow the section that addresses the properties of magnetic stacks. This decision was based on the fact that the construction of a magnetic stack out of small magnets in a way that the stack behaves like a single magnet is in line with the idea of the model of magnetic domains. This is evidenced by the fact that a stack formed by small magnets put together in a random manner appears to have less pronounced magnetic properties compared to stacks comprising magnets with properly aligned poles. This resonates well with the idea that non-magnetized ferromagnetic materials consist of magnetic domains pointing in random directions. In the revised version of the activity sequence, students are firstly engaged with the idea that magnets consist of aligned magnetic domains and, subsequently, they are guided to extend this idea in accounting for the magnetization of a ferromagnetic bar when it is placed in close proximity to a magnet. We thought that this would acquaint students with the opportunity to develop the model of magnetic domains on more solid foundations.

5.1.1.3 Indications for the Added Value Brought by the Revisions

The last two columns of Table 3 show the results of the categorization of students' responses to the same assessment task after the implementation of the revised version of the teaching-learning sequence, which incorporated the changes detailed earlier. As shown in these columns, there was a significant increase in the percentage of students who seemed to have developed coherent understanding of the model of magnetic domains and were able to apply it in accounting for how a ferromagnetic bar is magnetized (first category of response) (72 % compared to 32 % after the implementation of the initial version). Also, it is important to note that the vast majority of students (96 % compared to 64 % after the implementation of the initial version) provided responses that were classified under the first two categories, which happen to be the most informed. Clearly, these findings provide an encouraging indication as to the contribution of the revisions to the improvement of the effectiveness of the teaching-learning sequence.

5.1.2 Strength of a Magnet

5.1.2.1 Description of the Identified Limitation

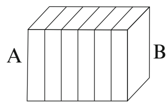
In Unit 4, students were asked to propose a method for comparing the strength of magnets of different shapes and sizes. The two most prevalent methods were the following: (1) counting the number of paper clips that the pole of a magnet was able to hold and (2) measuring the maximum distance at which a magnet was able to attract a stationary paper clip, causing it to accelerate towards one of its magnetic poles. These two methods were intended to serve as operational definitions for the notion of magnetic strength. The teaching-learning sequence departs from the premise that formulating and refining operational definitions are of paramount importance in science teaching in that they help students develop robust conceptual understanding (McDermott and The Physics Education Group at the University of Washington 1996). In the subsequent units of the teaching-learning sequence, students were expected to apply these two operational definitions for measuring the strength of several magnets, magnetic stacks, or electromagnets. An anticipated learning outcome of these activities includes the increased ability of students to reason about the strength of a magnet and the relative strength of different magnets. Also, these two operational definitions were expected to serve as useful resources in carrying out investigations of the extent to which certain factors affect the strength of a magnetic pole (e.g., what is the effect on the strength of each pole of a magnet after the magnet is cut into two pieces? How does the strength of each pole of a magnetic stack change after the addition of a new magnet?).

The analysis of students' responses to a relevant task intended to assess understanding of whether and how the strength of a magnet is influenced by changes in its size (summarized in Fig. 2) revealed specific difficulties, which are discussed next.

Table 4 shows the results of the categorization of student responses to this task. The first column summarizes the reasoning underlying each category, whereas the second column shows the percentage of the responses in each category after the implementation of an initial version of the teaching-learning sequence.

As shown in the second column of Table 4, 70 % of students expressed either the idea that changing the size of a magnetic stack (e.g., by removing some magnets) does not affect the strength of its poles (category 3) or the idea that the strength of the poles of each of two magnets that emerge from dividing a magnetic stack in two will be half the strength of the poles of the original stack (category 2). These two ideas imply that students tended to employ a heuristic model that portrays the strength of a magnet as a quantity that either is totally independent of the size of the magnet or changes with size in a linear manner.

A magnetic stack consisting of six magnets is able to hold a chain of 18 clips at each of its ends (A and B). The magnetic stack is stable.



If we split the magnetic stack into two equal pieces, each will be able to hold approximately:
i) 36 clips; ii) 18 clips; iii) 15 clips; iv) 9 clips

Explain your reasoning.

Fig. 2 Overview of an assessment task used for probing students' understanding of the strength of a magnetic stack (McDermott and The Physics Education Group at the University of Washington 1996)

Table 4 Understanding the strength of a magnet: categories of response and prevalence of each category prior to and after the proposed modifications

	Category of response	Categorization of students responses after the implementation of an initial version of the TLS N (%)	Categorization of students responses after the implementation of a revised version of the TLS N (%)
1	The strength of a magnetic stack does not increase additively.	17 (25 %)	20 (74 %)
2	The strength of the magnetic stack is equal to the sum of the strengths of the individual magnets that constitute the magnetic stack.	25 (38 %)	4 (15 %)
3	The magnetic stack has a constant strength; it does not depend on size or shape.	21 (32 %)	2 (7 %)
4	Irrelevant or incoherent responses	3 (5 %)	1 (4 %)

One reason which could account for the dominance of these non-valid responses relates to the approaches developed and employed by students for measuring the strength of a magnet. These approaches are very powerful in terms of helping students develop an operational definition for the strength of a magnet. However, at the same time, it is the case that the level of accuracy of the measurements they can yield is rather limited. It is restricted to rather rough estimates of the strength of magnets in that they typically fall short of detecting and quantifying, to a sufficiently large degree of precision, changes in the magnetic strength, especially changes that are small in magnitude.

5.1.2.2 Revisions That Had Been Undertaken to Address This Limitation

In revising the teaching-learning sequence, we decided to supplement the relevant part of the teaching-learning sequence with an activity that would enable students to take sufficiently accurate measurements of the intensity of the magnetic field through the use of a specialized instrument, namely, the magnetic field sensor. Thus, after students had been guided to develop and use the two procedures for measuring the strength of a magnet, they then proceeded to use this instrument for measuring the intensity of the magnetic field at any point around a magnet. The measurement was presented on the computer screen as an arithmetic value in Gauss units. The students used this sensor for measuring the intensity of the magnetic field at several points around a horse-shoe magnet and also to represent their measurements graphically. It is important to mention that special care was taken to usefully integrate this additional activity in the teaching-learning sequence. Specifically, we sought to ensure that students would be able to correctly interpret the measurements they were taking, associate those with the corresponding observations through the two procedures they had been guided to develop (operational definitions), and appreciate the facility of the sensor to supplement their observations, thereby enhancing their accuracy.

5.1.2.3 Indications for the Added Value Brought by the Revisions

Based on the empirical results that we collected after the implementation of the revised version of the teaching-learning sequence, it could be argued that the incorporation of the additional computer-based activities brought significant added value. Specifically, as shown in Table 4 (last column), the percentage of students who implied either that the intensity of the magnetic field changes as the size of the magnetic stack changes, in a linear manner, or that it is not influenced by changes in size underwent a substantial reduction (from 70 % to 22 %). Also, it is worth noticing the significant increase in the percentage of the students who were able to give a correct response (74 % compared to 25 % in the implementation of the initial version of the teaching-learning sequence), as illustrated in the following extract from a student response:

> We learnt that by adding a magnet to another one their strength will increase but it does not increase additively. This pattern holds until the point where adding another magnet does not actually change the strength, because it has reached its limiting value. So, if we split a magnetic stack into two pieces, their strength will be lower, but higher than half the strength of the initial stack.

5.2 Limitation II: Transfer of Concepts to the Process of Designing and Constructing the Train Model

The second type of limitation that was identified pertains to the facility of the teaching-learning sequence to promote the transfer of concepts and principles addressed in its first part (conceptual elaboration of electromagnetic properties of materials) to the process of designing and constructing the train model, which took place in the second part. Next, we elaborate on two specific examples of this limitation.

5.2.1 Magnetic shielding

5.2.1.1 Description of the Identified Limitation

One of the main specifications that students were expected to address in designing their train models was the provision of "magnetic shielding" so as to minimize, to the extent possible, passengers' exposure to the magnetic field and the associated health risks. After students had been guided to construct the model of magnetic

Table 5 Artefact analysis of train models and posters from two implementations in relation to the magnetic shielding specification

	Approaches adopted for achieving magnetic shielding	Data from the analysis of the posters from the implementation of an initial version of the TLS	Data from the analysis of the posters from the implementation of a revised version of the TLS
1	Use of a ferromagnetic material inside the wagon for magnetic shielding purposes. Elaboration of the magnetic shielding mechanism and reference to the corresponding inquiry activity	12 %	54 %
2	Use of a ferromagnetic material inside the wagon for magnetic shielding purposes. No elaboration of the magnetic shielding mechanism	12 %	28 %
3	Use of a diamagnetic material inside the wagon for magnetic shielding purposes. Elaboration of the magnetic shielding mechanism (magnetic field is attenuated by the diamagnetic material)	25 %	11 %
4	Use of a material inside the wagon which does not affect the magnetic field. No reference to the magnetic shielding mechanism	13 %	5 %
5	No material has been used inside the wagon of the train. No reference to the magnetic shielding mechanism	38 %	2 %

domains, they were engaged with exploring the facility of various materials to attenuate the magnetic field around a magnet. In doing so, they tied a paper clip on a string, and they used a magnet to attract the paper clip from a distance so as to make the string taut. Then they placed various sheets of different materials, one at a time, between the magnet and the paper clip. They used materials such as plastic, wood, aluminum, copper, iron, or steel, and they were asked to identify which materials triggered the paper clip to fall. They were expected to observe that sheets of ferromagnetic material produced a screening effect, reducing the intensity of the magnetic field at the other end. It was assumed that students would be able to readily draw on the results of this activity while designing their train models in the second part of the teaching-learning sequence. This, however, was not the case. Table 5 summarizes the results of the artefact analysis of the train models with respect to the feature of magnetic shielding. The first column provides an overview of the different approaches taken by students to address the issue of magnetic shielding, and the second column shows the percentage of the groups of students who followed each approach during the implementation of a version of the teaching-learning sequence that included the initial activity sequence dealing with the attenuation of the magnetic field. As shown in this column, only a limited number of groups of students chose to cover the bottom of their wagons with ferromagnetic materials, whereas the majority used either diamagnetic materials or nothing at all. Also, it is important to note that only in one of the posters created by the groups that chose to use a ferromagnetic material did students invoke the evidence they had collected during their investigations as a means to justify their choice. Clearly, these findings suggest that students were not well positioned to draw on the observational data they had collected in terms of the facility of various materials to attenuate magnetic field, as a resource for informing their design decisions on how to address the feature of magnetic shielding.

5.2.1.2 Revisions That Had Been Undertaken to Address This Limitation

In an attempt to address this limitation, we revised the activity that pertains to the exploration of whether various materials could serve to attenuate the magnetic field, so as to make it more explicit. In the revised version, students were asked to obtain two small plastic sheets and tie them with the use of tape in such a way that they are separated by a small gap. They were then asked to fix a small disk magnet on the one side and bring some paper clips close to the other side until they get attracted by the magnet. In the next instance, they were asked to insert sheets made of different materials (e.g., plastic, wood, aluminum, copper, iron, etc.) in the gap, one at a time, and observe how this influences the system of the magnet and the paper clips. Again, students were expected to observe that only sheets of ferromagnetic material triggered the paper clip to fall. They were then guided to reflect on what these observations seemed to be suggesting about how the strength of the magnetic field changes as a result of the presence of each type of material. The incorporation of this reflective exercise was expected to better prepare students to use the implications stemming from these observations, in reasoning about how to address the issue of magnetic shielding during the design and construction of their train model in the second part of the teaching-learning sequence.

5.2.1.3 Indications for the Added Value Brought by the Revisions

The analysis of the artefacts constructed by students' (e.g., posters and train models) during the implementation of the revised version of the teaching-learning sequence, which are shown in the last column of Table 5, indicates a considerable increase of the percentage of groups of students that chose to use a ferromagnetic material to cover the bottom of the wagons of their train models that (first two rows of Table 5). It is interesting to note that more than half of these groups of students were also able to account for the mechanism underlying magnetic shielding (e.g., the lines of the magnetic field follow the surface of the ferromagnetic material and return back to the magnet). Most importantly, they frequently included explicit references to the observational data they had encountered during the corresponding inquiry activity (e.g., experimental investigation of the materials that impact on the magnetic field), which indicates that they became better positioned to transfer and apply the conceptual ideas they had encountered in the first part of the teaching-learning sequence.

5.2.2 Propulsion Mechanism

5.2.2.1 Description of the Identified Limitation

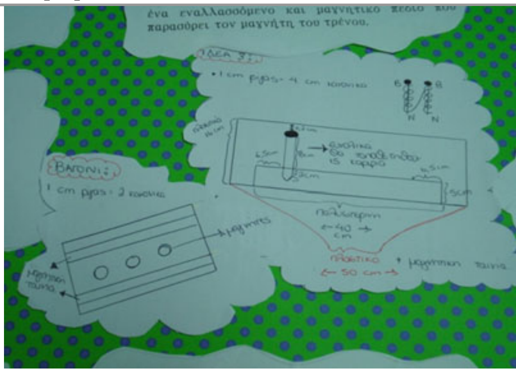
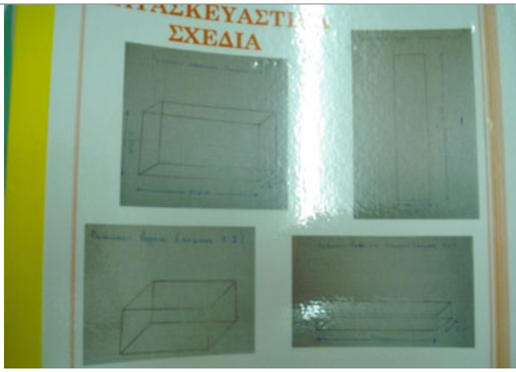
Achieving self-propulsion required students to develop a mechanism based on electromagnetic interaction. Unit 4, which focuses on "electromagnets," is intended to help students develop key ideas that would enable devising such a mechanism. Specifically, in this unit, students are guided to observe that the magnetic field created around a current-carrying wire wrapped in the shape of a coil has the same form as that of a bar magnet. Also they are guided to explore the properties of electromagnets and investigate the influence exerted by various factors on their strength. At a subsequent stage, during the design and construction on the train model, students were expected to experiment with reversing the polarity of electromagnets placed upright in parallel and observing how this impacts on the motion of the train.

The results of the artefact analysis demonstrated that students fell short of providing adequate accounts of how key ideas relevant to electromagnetic interactions could be drawn upon in devising an effective propulsion mechanism. This failure was evident in students' posters, in that they were mostly limited to superficial descriptions about the construction of the train model, which excluded important information on how propulsion had been achieved. Table 6 provides two illustrative examples. This finding indicates that students might have not developed a deep understanding of the properties of electromagnets that need to be taken into account for the development of a propulsion mechanism.

5.2.2.2 Revisions That Had Been Undertaken to Address This Limitation

Based on the findings from the implementation of the initial version, we decided that it should be useful to enrich the part of the teaching-learning sequence related to electromagnets and address the targeted ideas more explicitly. The first revision that was undertaken includes the incorporation of an activity intended to help students appreciate the idea that the polarity of an electromagnet depends on the direction of the current that flows through the coil. Students were asked to construct two electromagnets with different coil orientations (clockwise and anti-clockwise) along the length of a nail (from head to tip) and examine their polarity. An additional activity was aimed at offering students the opportunity to explore the idea of how motion can be achieved through electromagnetic interaction and to figure out the underlying principles of this mechanism. In this activity, students were asked to place two electromagnets perpendicularly to a wooden surface and connect them

Table 6 Typical examples of how the propulsion mechanism was represented in students' posters

	Description and representation of the propulsion mechanism	
1	"Electromagnets are placed in a row and they are supplied with current in order to produce a magnetic field. The electromagnets interact with disk-shaped magnets under the wagon."	
2	The rail and the wagon are presented in a drawing in which the dimensions of each are depicted, but no explanation about the propulsion mechanism is provided.	

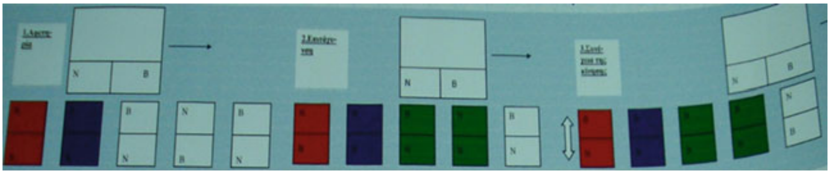
with a battery in such a way that the two electromagnets have opposite polarity at the side of the wooden surface. While the circuit was still open, a small disk magnet was placed on the other side of the surface between the two nails. When the circuit was closed, students observed the magnet moving towards one of the two nails. Then, the polarity of both electromagnets was reversed, and the disk magnet moved towards the other nail. Students were asked to record and account for their observations.

In addition to incorporating these supplementary activities, another vitally important revision included the provision of structure and scaffolding to students so as to engage in explicit, reflective discussions about the results of these activities and possible ensuing implications for the design of the train model.

5.2.2.3 Indications for the Added Value Brought by the Revisions

The analysis of the posters constructed by the students after the implementation of the revised version revealed a significant improvement in their ability to transfer ideas and findings from the first part of the teaching-learning sequence to the second, i.e., the technological project. In particular, students became more likely to come up with effective designs in terms of the propulsion mechanism, by manipulating the interactions between electromagnets along the rail and magnets under the wagon. Also, their descriptions of the propulsion mechanism became much more detailed and elaborate. The following descriptions of the propulsion mechanism, extracted from two different posters, are particularly revealing:

> The red electromagnet has the same polarity with the blue one (see Picture below) in order to move the wagon forward by repelling the magnet under the wagon. So the train moves over the green electromagnets, which attract its magnets. Then, the direction of the current is reversed and the electromagnets change polarity. Since the wagon has already gained velocity, it will keep moving forward and its velocity will depend on the frequency of the alternating current.



> When current runs through the coils, the magnets of the wagon will be repelled by the like poles of the corresponding electromagnets that are underneath them. At the same time, each one will be attracted by the opposite pole of the next electromagnet and the magnet will move towards it. Since the power source provides alternating current, the polarity of the electromagnets will be changing continuously and the wagon will be repelled from the new position and get attracted to the next one.
>
> For the construction of powerful electromagnets we chose to use (i) iron nails which are easily magnetized, (ii) thin wire in order to be able to make dense coils, and (iii) as high intensity of current as possible.

5.2.3 Limitation III: Extent of Engagement With the Technological Design and Construction Process

An additional type of limitation that we identified relates to the extent to which the teaching-learning sequence provided students with sufficient support to effectively engage in the process of designing and constructing the train model. The aim of the teaching-learning sequence at this stage was twofold; students were expected to (1) become familiar with fundamental components involved in the process of designing and constructing technological products (e.g., the train model) as solutions to specified problems (e.g., specifications to be satisfied by the train model, namely, propulsion, levitation, and magnetic shielding) and (2) transfer and transform conceptual ideas addressed in the first part, in making decisions about the optimum design that could meet the targeted specifications. We drew on both students' constructed train models and their accompanying posters as a means to derive indications as to the extent to which these goals were promoted through the teaching-learning sequence and also to identify possible difficulties that hampered students' attempt to come up with effective designs of the train model.

5.2.3.1 Description of the Identified Limitation

At an early stage in the sequence of the various implementations of the teaching-learning sequence, it became obvious that students were often not effectively or genuinely engaged with the design process. In particular, their work tended to be restricted at a rather superficial level, failing to reflect thoughtful engagement with the various components involved in the design process. For instance, their engagement with the design and construction of the train model was rather unsystematic in that they even entirely skipped important components of the design process, such as the evaluation of the train model and the identification of possible ways of improving it so as to better meet the targeted specifications. Also, in constructing their posters, they often restricted themselves to merely copying information from the description of the design project that was included in the teaching-leaning sequence. This tendency to adopt surface strategies could be attributed to the possible failure of the teaching-learning sequence to help students assume ownership of the design task.

5.2.3.2 Revisions That Had Been Undertaken to Address This Limitation

In revising the teaching-learning sequence, we essentially sought to incorporate components that would (a) provide students with increased structure for implementing the technological design project and (b) increase the likelihood for them to actually engage with this process in a meaningful and thoughtful manner. The first revision we undertook towards this end involved placing increased emphasis on helping students articulate specific criteria for peer-evaluation and self-evaluation of their current work throughout the design process. These criteria were directly linked to the targeted specifications. Students were engaged in systematically employing these criteria for evaluating their train model.

The second revision included the incorporation of various prompts throughout the design process, so as to help students explicitly identify and discuss in their groups important issues regarding the design of the train models. This was essentially intended to strengthen the connections between the first part of the teaching-learning sequence (i.e., conceptual elaboration of electromagnetic properties of materials) and the second part (i.e., design and construction of the train model). For instance, at the stage where students were engaged in the process of clarifying the technological problem they had to address, they were asked not only to identify the specifications that should be satisfied by the design they would come up with (e.g., magnetic levitation, electromagnetic propulsion, and magnetic shielding) but also to explicate and elaborate the mechanisms they would devise so as to meet these specifications. In addition to this, we also included probes specifically targeted at keeping students accountable and promoting reflection at the group level. Some examples of these probes include the following:

- *How did others solve the same problem or a similar problem?*
- *What information did you find about the materials needed (cost, aesthetics, ergonomics, etc.)?*
- *What mechanisms did other people use in order to accomplish the three operations (levitation, propulsion, shielding)?*

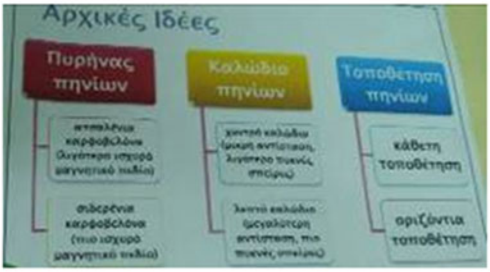
An additional example of an activity we incorporated for promoting reflection involved engaging students in elaborating the practical (or other) difficulties that hampered their attempt to design and construct the train model and identify possible changes they would make if they were to repeat this technological project. Also, they were asked to reflect on specific limitations of their train models, in terms of their facility to satisfy the targeted specifications, and identify possible amendments. The aim was to reflect on the process they had followed, identify possible weaknesses, and suggest corresponding refinements. Through this reflective exercise, we anticipated that students would come to understand that technological design is an iterative process which aims at the development, evaluation, and refinement of a technological product so as to better fulfil the targeted specifications.

5.2.3.3 Indications for the Added Value Brought by the Revisions

Evidence from the analysis of the posters prepared by students in an implementation of the revised version of the teaching-learning sequence revealed that they became better positioned to productively engage with the technological design process. This was evident from the early stages of the technological process (e.g., description of the problem to be addressed and formulation of the corresponding specifications). In most cases (16 out of 17 groups in one of the implementations of the revised version of the teaching-learning sequence), students provided elaborated accounts as shown in the following extract:

> Transportation in Cyprus is a severe problem, not only for the economy of the country because of the high cost of fuel, but also for the environment and public health. Having this in mind, we are asked to develop a novel train model, based on new technological advances, as a possible solution to the transportation problem. In order to ensure that our train will be economic, environmentally friendly, fast and safe for its passengers, the following specifications need to be met:
>
> – Magnetic levitation
> – Electromagnetic propulsion
> – Magnetic shielding

We also encountered elaborate accounts in students' descriptions on how they would go about solving the technological problem. Some groups suggested the use of electromagnets placed horizontally and the use of permanent magnet(s) underneath the train wagon as the mechanism of propulsion. An example of this case is presented in Fig. 3, illustrating how the students had organized their initial ideas



[English translation]

Core of the electromagnets

- Stainless steel – the "strength" of the magnetic field is lower than in the case of iron.
- Iron - the magnetic field produced is stronger

Wire

- thicker wire – lower resistance, fewer loops
- thinner wire – higher resistance, more loops

Position of the Electromagnets

- vertical
- horizontal

Fig. 3 An example from a poster that illustrates the formulation of alternative ideas

with respect to three important aspect of the design (i.e., material for the core of the electromagnet, type of wire and position of the electromagnets) and provided possible options for each.

In most cases, students selected to make drawings so as to convey a clearer idea about how each of the three mechanisms was to be accomplished. Figure 4 provides an example of such a drawing that illustrates the way the wire is wrapped around the nails to form a coil and how two adjacent coils are connected.

Finally, most of the posters incorporated a section referring to the test and evaluation of the final product in conjunction with (1) descriptions of the procedure followed for testing the train model on each of the required mechanisms, (2) information about the results of these tests, and (3) suggestions of ways of overcoming identified shortcomings. Figure 5 provides an example of (a part of) a poster in which students identify possible reasons why their train did not behave as desired and allude to possible amendments so as to alleviate these shortcomings.

Overall, the analysis of students' posters indicates that the revisions that had been undertaken in an attempt to systematize the implementation of the design project did increase accountability and enhance the quality and depth of students' engagement with the design project.

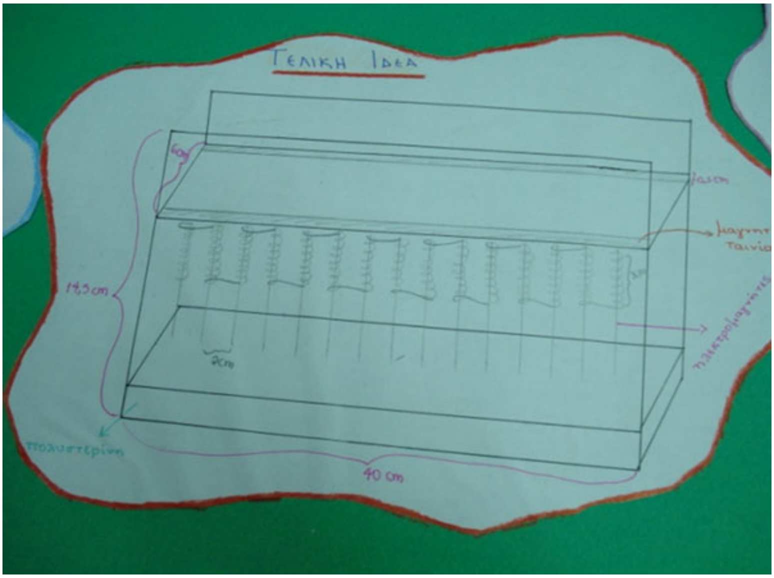
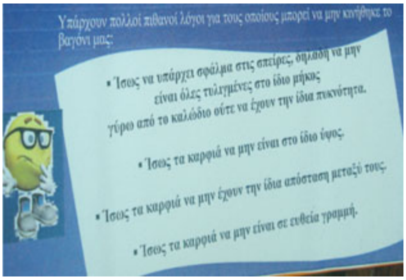


Fig. 4 A drawing representing the connection among the coils for accomplishing the propulsion mechanism



[English translation]
There are a lot of possible reasons that could account for the failure of our wagon to move as desired:
There might be some fault within the coils, e.g. the length of the wire that each coil has been made of, is not constant.
The nails might not have had exactly the same height.
The distance between the nails making up the cores of the coils is not equal.
The nails of the coils are not aligned.

Fig. 5 An example from a part of a poster referring to the evaluation of the train model

5.2.4 Limitation IV: Epistemological Awareness concerning the Distinction and Interconnection between Science and Technology

The properties of materials and their influence on the material selection process for various applications offer a productive context for epistemologically rich discussions on the interconnections between science and technology and their role in modern society. The initial version of the teaching-learning sequence did not seize the opportunity to actually engage students in explicit epistemological discourse about the distinction between science and technology and their connections. It was somehow assumed that students' extensive engagement with the conceptual elaboration of magnetic and electromagnetic phenomena, on the one hand, and the application of the relevant conceptual ideas during the implementation of the technological project, on the other hand, would suffice to bring about improvements in their epistemological understanding about the distinction and interrelationship between science and technology. However, as discussed next, this was not the case. The empirical data we have collected revealed that students' extensive interaction with processes of scientific inquiry and technological design is not a sufficient condition for developing epistemologically informed ideas in this respect.

5.2.4.1 Description of the Identified Limitation

One of the tasks that we used to assess students' understanding of the distinction and interconnections between science and technology provided them with brief descriptions of the objective pursued by a variety of research projects. Those descriptions were formulated so as to either present instances of objectives exemplifying the overall goal of either science (i.e., improvement of our understanding of a phenomenon – e.g., *we observe the sky through telescopes in order to study the motion of planets*), technology (i.e., construction of a solution to a specific problem – e.g. *we try to make an artefact that could protect us from lightning*), or neither of the two fields (e.g., *we are trying to decide the best location to install a desalination plant*). Students were first asked to state whether the goal of each research project was more consistent with science, technology, or neither. In the next instance, they were asked to formulate a rule that could serve as a demarcation line between the two fields. Next, we describe students' responses to this latter open-ended probe.

The analysis of students' responses to this open-ended probe led to the identification of five categories of response. These are outlined in the first column of Table 7. The next two columns present the frequencies and percentages of the responses falling under each category prior to and after the implantation of a version of the teaching-learning sequence that did not incorporate explicit epistemic discourse. The last two columns show the results of the categorization of students' responses prior to and after the implementation of a subsequent version of the teaching-learning sequence that did incorporate this element.

The first category, which happens to be the most informed, includes responses that distinguished between the two fields on the basis of the goal they pursue. This category appeared in two variants. In both cases, students explicitly referred to the goal of science being the enhancement of our understanding about how the natural world operates and the goal of technology being the construction of a solution to a given problem. The difference between these two variants is that, in the first case, students seemed to appreciate the improvement of understanding per se as a useful and worthwhile end on its own right. An example of a response from this category is the following: “A project belongs to science when it deals with natural phenomena and studies them in depth so as to establish theories. A project belongs to tech-

Table 7 Categorization of students' responses to the assessment task for the distinction between science and technology

	Data from the implementation of an initial version of the TLS		Data from the implementation of a revised version of the TLS	
	Pre-test	Post-test	Pre-test	Post-test
Categories of response	N (%)	N (%)	N (%)	N *(%)*
1. Discriminating based on the goal of each field	13 (50 %)	12 (46 %)	4 (11 %)	23 (62 %)
Subcategory 1.1: Science tries to understand how the natural world functions. Technology tries to intervene on the natural world by inventing solutions to problems and addressing human needs.				
Subcategory 1.2: Science seeks to explain why something happens in order to find the solution to a problem and serve humanity. Technology seeks to implement this solution or to contribute towards developing this solution through some construction.				
2. Discriminating based on the object of study in each field	-	5 (19 %)	16 (43 %)	5 (14 %)
3. Discriminating based on the methods employed in each field	3 (12 %)	2 (8 %)	3 (8 %)	-
4. Inadequate or ambiguous discrimination	8 (30 %)	7 (27 %)	6 (16 %)	5 (13 %)
5. Irrelevant response	2 (8 %)	-	8 (22 %)	4 (11 %)

nology when it tries to develop solutions to specified problems with the intent to address human needs and improve our life." In the latter variant, they explicitly linked the improvement of understanding with the solution to a particular problem. For example, one of the students who responded in this way stated that "[a] project belongs to science when the goal is to develop knowledge. A research study belongs to technology when it tries to construct something that will solve a specific problem, utilizing scientific knowledge." Thus, in this latter case, students referred, or alluded, to a specific one-way connection between science and technology: science produces the knowledge needed for the development of technological solutions to given problems.

The second category comprises the students who had focused on the characteristics of what is under study in each case. Inherent in these responses was the assumption that science deals with natural objects (objects directly derived from nature), whereas technology deals with the artificial environment (objects built or processed by humans). This is illustrated in the following example: "When it relates to a living organism, the research belongs to the field of science. When it relates to electronics or stuff made by people, then it belongs to the field of technology."

Students who were included in the third category focused instead on the methods employed in the two fields. They tended to exclusively associate experiments with science and to reduce technology to specific processes such as construction, calculation, and measurement. For instance, one student wrote that "[a] project belongs to science when somebody conducts an experiment. A research project belongs to technology when we construct something."

Students in the fourth category essentially fell short of proposing specific criteria for distinguishing science from technology. They either provided vague descriptions or restricted themselves to statements referring to only one of the two fields. Finally, the last category involved cases in which students failed to address the question at hand. For instance, one of these students stated that "[i]n science we do scientific stuff and in technology we do technological stuff."

As shown in the third column of Table 7, the percentage of responses that were classified in the first category, which reflects the most informed notion of the distinction between science and technology that we sought to promote, is somewhat low (46 %). This provides an indication as to the limited impact of students' interaction with the teaching-learning sequence on their understanding of the distinction and inter-relationship between science and technology.

5.2.4.2 Revisions That Had Been Undertaken to Address This Limitation

The main revision that we undertook so as to address this limitation involved the incorporation of activities that engaged students, in a systematic manner, in explicit epistemological discourse about the distinction and interrelationship between science and technology. These instances of structured engagement with explicit epistemic discourse were dispersed throughout the teaching-learning sequence, and care was taken to integrate them with the activities undertaken by students either while elaborating conceptual ideas relevant to the behavior of magnets/electromagnets or while designing and implementing the technological project. For instance, students' elaboration of the idea of the magnetic field and, subsequently, the model of the magnetic domains were deemed appropriate contexts for engaging students in epistemic discourse intended to help them identify conceptual models as human constructs which have been invented in science in the pursuit of coherent theoretical frameworks that could facilitate the interpretation of physical phenomena and the prediction of the operation of relevant physical systems. Another example relates to the activities that engaged students with the design and conduction of experiments so as to investigate whether (and how) various factors influenced the strength of an electromagnet. This context was taken advantage of so as to engage students in epistemic discourse about the importance of designing unconfounded experiments as a core mechanism of testing hypotheses in science. In a similar manner, while engaging with the design and construction of the train model, students were guided to appreciate *design* as a core process of technology. Finally, at the end of the design project, students were explicitly asked to reflect on instances they encountered throughout the teaching-learning sequence that could be revealing of possible connections between science and technology. In doing so, we expected students to be able to identify that the first part of the teaching-learning sequence helped them build understanding of the operation of systems involving electromagnetic properties of materials, which, in turn, substantially informed the process of designing and constructing the train model. We expected that they could conceive of this as an example illustrating the facility of science to provide conceptual tools that could support and inform the development of relevant technological products. In addition, we also expected students to identify instances in which technology provides helpful tools that could enhance our ability to take reliable and accurate measurements for physical quantities, such as the sensor used for measuring the strength of the magnetic field. Through these embedded discussions, students were systematically engaged with explicit epistemological discourse, which we deemed important for facilitating the promotion of the corresponding learning objectives (appreciation of the distinction and connections between science and technology).

5.2.4.3 Indications for the Added Value Brought by the Revisions

The last two columns of Table 7 show the results of the categorization of students' responses to this same assessment task, after the implementation of the revised version of the activity sequence. As shown in these columns, there was a considerable increase in the percentage of responses in the first category (62 % compared to 46 %) and a corresponding decrease in the percentage of students who either gave non-valid responses or failed to even draw a distinction between the two fields. This finding provides an encouraging indication with respect to the increased facility of the teaching-learning sequence to promote students' epistemological awareness concerning the distinction and interconnections between science and technology and help them overcome difficulties they might encounter with respect to these issues (e.g., exclusively associating experiments with science, thereby dismissing their vitally important role in the field of technology).

6 Discussion

In this chapter, we reported on the process of the refinement of a teaching-learning sequence on the topic of electromagnetic properties of materials, and we particularly focused on how the accumulated empirical evidence about the corresponding student learning outcomes has been used to guide the refinement process. The teaching-learning sequence has been exposed to a number of implementation-evaluation-revision cycles. During each enactment, we collected empirical data on students' learning gains with a view to use that as a basis for the refinement of the teaching-learning sequence. Specifically, these data provided indications not only for aspects of the activity sequence that seemed to have functioned to a satisfactory extent but also for parts of the activity sequence that did not function quite effectively. This latter source of data guided the refinement process of the activity sequence, so as to further enhance its potential to promote the learning objectives it has been designed for. Specifically, the findings presented in the study revealed four types of limitations in terms of the facility of the teaching materials to help students attain the targeted learning objectives. The first type of limitation concerns students' inadequate *conceptual understanding* of various important ideas related to magnetism and electromagnetism; the second type pertains to the difficulties in transferring and effectively applying conceptual ideas in the process of designing and constructing the electromagnetic train model; the third type of limitation relates to the support (or lack thereof) provided to students for productively and effectively engaging with the *design process*; the fourth type of limitation refers to the limited impact on students' epistemological awareness about the distinction and interconnections between science and technology. The identification of these limitations has led to a variety of revisions intended to enhance the potential of the teaching-learning sequence to address its targeted learning objectives. To reiterate, these revisions include (1) integrating ICT tools (e.g., data logging software and equipment) within specific activities, so as to take advantage of the added value of the capabilities offered by these tools; (2) supplementing existing activities with specially designed probes aimed at increasing student reflection and offering structure or scaffolding for performing certain tasks (e.g., on how to ensure appropriate design of valid experiments), (3) rearranging parts of the activity sequence so as to increase coherence; and (4) incorporating explicit epistemological discourse about the connection and distinction between science and technology. Table 8 summarizes the revisions that have been undertaken in our attempt to use evaluation data in order to refine the teaching-learning sequence. The table summarizes all the revisions that have taken place, including those not elaborated in this case study. Indicatively, some of these additional revisions include (1) the removal of time-consuming activities that were associated with a demonstrably limited contribution to the attainment of the targeted learning objectives; (2) the interjection of additional activities as needed so as to either help students address specific difficulties (e.g., conceptual, procedural, or epistemological) identified in various phases of the implementation of the teaching-learning sequence or serve as stepping stones that could bridge gaps in the activity sequence.

6.1 Implications for the Process of Developing Curriculum Materials

The development of curriculum materials should best be described as a process that largely draws on empirical research. Any attempt to develop curriculum materials needs to incorporate an empirical component, which could serve to provide

Table 8 Initial and revised version of the activity sequence of the module

		Learning objectives	Type of change
Students should be able to:			
Unit 0	Design project remit	Identify the main aspects of the remit and (1) identify required knowledge and (2) develop a plan of work	
Unit 1. Investigation with magnets	Section 1. Magnetic interactions	Familiarize with the notion of magnetic interaction (attraction/repulsion)	
		Describe a process for distinguishing magnets from ferromagnetic materials – operational definition of a magnet	
	Section 2. The parts of a magnet	Understand the behavior of different parts of a magnet	
		Describe a process for recognizing the poles of a magnet	
	Section 3. The earth as a magnet	Appreciate the earth as a large magnet and differentiate between magnetic and geographic poles	Removal of activity
		Identify poles (north & south)	
		~~Give directions taking into account the magnetic declination~~	
	Section 4. Comparing the strength of magnets	Distinguish between "strength" and "size" of a magnet	
Unit 2. Magnetic interactions at a distance	Section 5. Magnetic field model	Understand the abstract concept of the magnetic field	Rearrange the order of activities (sections)
	(This section was initially Section 6)[a]	Represent the magnetic field for magnets of different shape	Introduction of new learning objectives *(procedural skills, epistemological awareness)*
		Appreciate the magnetic field as a tool for explaining interactions at a distance	

(continued)

Table 8 (continued)

		Learning objectives	Type of change
		Identify the characteristics of a magnetic field (direction and density of magnetic field lines)	Design and incorporation of additional learning activities to promote the new learning objectives
		Measure the strength of magnets using appropriate techniques/ instruments	
		Understand and appreciate the role of models in science	Integration of ICT tools within specific activities
Unit 3. A Model for magnetic materials	*Section 6. Breaking and forming stacks of magnets (This section was initially Section 5)*	Understand the behavior of a magnetic stack	Rearrange the order of activities (sections)
		Explain how the "strength" of a magnetic stack changes as magnets are added in the stack	Integration of ICT tools within specific activities
		Decide about the arrangement of individual magnets to develop magnetic stacks with maximum "strength"	Modification of a specific activity to address the corresponding learning objective in a more explicit and effective manner (reasoning strategies)
	Section 7. A model for magnetic domains	Account for magnetization and demagnetization through a conceptual model of magnetic domains	Modification of a specific activity to address the corresponding learning objective in a more explicit and effective manner *(conceptual understanding)*
		Identify materials that attenuate the magnetic field	

(continued)

Table 8 (continued)

		Learning objectives	Type of change
Unit 4. Investigation with electromagnets	Section 8. Magnetic field of a current-carrying wire	Understand that a current-carrying wire creates a magnetic field and identify its shape and direction	
	Section 9. Making magnets with a current-carrying wire	Explore possible ways of creating electromagnets and identify their properties	Introduction of new learning objectives *(conceptual understanding, procedural skills)*
		Identify the shape and *determine the polarity of the magnetic field of electromagnets*	
		Attaining propulsion using electromagnets	Design of additional learning activities to promote the new objectives
	Section 10. Scientific investigation with electromagnets	Design experiments to investigate the variables that might affect the strength of an electromagnet (variable control strategy)	Introduction of new learning objectives (*epistemological awareness*)
		Understand and appreciate investigation as a core process of science	Design of additional learning activities to promote the new objectives
Unit 5. Technology project: Mag-Lev train	Section 11. *Design and construction of a Mag-Lev train model*	Transfer conceptual ideas to the design of the train model	Modification of a specific activity to promote the corresponding learning objective in a more explicit and effective manner (*technological design skills and knowledge*)
		Appreciate essential processes involved in the design and development of a product (train)	
		Differentiate between scientifically & technologically oriented goals	
		Differentiate between the main processes of these two fields	Introduction of new learning objectives (*epistemological awareness*)
			Design of additional learning activities to promote the new learning objectives

(continued)

Table 8 (continued)

		Learning objectives	Type of change
Unit 6. Science and technology: Two distinct fields	***New Section*** *: Section 12. Interrelationship and differences between science and technology*	*Understand the bidirectional relationship between science & technology and their main difference*	Introduction of new learning objectives (*epistemological awareness*)
			Design of new learning activities to promote the new learning objectives

Notes

[a]The text that appears in *italics* refers to a *revision* in teaching-learning sequence, which was undertaken after a specific implementation

[b]The text that appears in ~~strikethrough~~ refers to an activity that was deleted from the teaching-learning sequence

indications about their potential effectiveness. As shown in this study, the possible limitations could vary substantially in nature and one needs to anticipate (and be attentive to) this variation. This empirical component of the curriculum development process could support evidence-based decision-making on how to go about refining the activity sequence. This part of the process needs to be iterative; it should allow returning to the drawing board as many times as necessary so as to modify either individual activities or the entire sequence. The iterative, empirical exploration and refinement of the various elements of teaching innovations, like the teaching-learning sequence presented in this study, provide a powerful framework for developing research-validated teaching-learning sequences. In addition to refining the teaching-learning sequence, this empirical component can also contribute to the enhancement of our theoretical understanding about relevant learning phenomena. Next, we seek to illustrate this by discussing specific implications for science teaching and learning that seem to emerge from the data reported in this study.

6.2 Implications for Science Teaching and Learning

6.2.1 Shifting Away From Factual Knowledge towards Coherent Conceptual Understanding

As has been amply documented in the research literature, coherent conceptual understanding appears to be a rare outcome of conventional teaching (McDermott 1993). This is directly related to the tendency of traditional teaching to place the emphasis on factual, declarative knowledge and the corresponding tendency to employ a content delivery teaching approach. This study provides indications for two specific design features that could facilitate the shift towards teaching for coherent conceptual understanding. The first relates to the importance of helping students really appreciate the interpretive and predictive capability of the conceptual models they are guided to construct. In designing the teaching-learning sequence, we identified specific core ideas that we would like students to attain (e.g., magnetic domain, magnetic field, and magnetic stuck) and we ensured that the teaching-learning sequence would guide students, through a process of inquiry, to make specific observations and develop the targeted ideas as conceptual tools that could help accounting for these observations. For instance, the magnetic domains model serves as a means to account for the magnetization/demagnetization of ferromagnetic materials, whereas the magnetic field presents a means to account for magnetic interactions at a distance. Much emphasis is placed on engaging students in applying these conceptual tools for the analysis of unfamiliar systems. This emphasis on highlighting the value of the various conceptual ideas elaborated through the teaching-learning sequence in interpreting and predicting the behavior of relevant systems could probably be conducive to coherent conceptual understanding. The second teaching strategy relates to the opportunity provided to the students to transfer and apply recently gained science conceptual understanding to a relevant technological problem-solving task. This integration of the elaboration of science domain knowledge with a relevant technological project could be a powerful teaching scheme in that it enables students to consolidate their learning achievements and build confidence about their understanding. In addition, it could help students appreciate the relevance of the concepts they develop to a specific problem-solving situation.

6.2.2 Theorizing From Specific Examples as a Teaching Strategy

The teaching-learning sequence seeks to help students develop fundamental ideas relevant to magnetism and electromagnetism and then engages them in applying these ideas in the design and construction of a model of a magnetically levitated train. Within this project, they also use instruments to undertake specific measurements (e.g., intensity of the magnetic field inside the wagon) so as to evaluate the extent to which the model satisfies the targeted specifications (e.g., magnetic shielding). This provides an appropriate context for situating the elaboration of specific ideas, such as the distinction between science and technology and their possible interactions (e.g., science informs the design process, technology provides measurement instruments that could be used in undertaking investigations). Situating the elaboration of such conceptual and epistemic ideas in a specific concrete example and drawing generalizations from that (e.g., the connections between science and technology addressed in the design project could be broadly applied to other relevant situations) could be a powerful teaching and learning process for developing coherent understandings.

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Concluding Remarks: Science Education Research for Enhancing Classroom Learning

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The Social Sciences undertake a dual role. On the one hand, they take on the responsibility to study the phenomena relating to human interactions and, through these studies, to contribute to our knowledge of the underlying mechanisms in a way that is coherent and generalizable, to the extent possible. On the other hand, they also take on the responsibility to contribute, through local action, to the organization and function of systems that tend to be highly local in their features and often contextualized in their intents.

Science education research is characteristically distinctive among the social sciences in that, in its efforts to address teaching-learning problems and to develop our understanding of processes and outcomes of the educational effort, it has taken advantage of the broad global consensus on the contents of science in order to develop broadly applicable methodological tools and innovations. Among these, teaching-learning Sequences (TLSs) have emerged as a construct that mediates between research and classroom practice in a way that can respect teacher action as a scientific activity, while at the same time providing theoretical input to inform practices and reflections on their outcome.

This book highlights a number of examples of researcher-teacher collaborative efforts to design, develop, refine, and also share TLSs across a range of European educational systems, abstracting both process and content principles that would be applicable beyond the confines of these individual efforts or their contexts (Part III

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Case Studies). A series of theoretical chapters also formulate a number of important aspects of TLSs as a construct that can mediate effectively between theoretical and classroom perspectives (Part I Theoretical Aspects). An overview of developments and trends with regard to teaching-learning sequences and their classroom implementation, discussing empirical studies, suggested design frames, methodological tools, and approaches to describing the design of these sequences, their commonalities and differences; and their relation to design-based research is provided in the chapter by D. Psillos and P. Kariotoglou. The importance of iterative refinement and empirical research as processes for validating the structure and content of TLS are highlighted in this chapter. The issue of relating science and technology in its broad sense is taken up by I. Testa, S. Lombardi, G. Monroy, and E. Sassi who propose a research-based framework aiming at integrating science and technology, which identifies a common science and technology core, namely, the scientific investigation and modeling of natural phenomena and the harnessing of basic physics in technological objects. The value of equitable participative approaches, in which teachers utilize their own expertise to influence the structure and content of a TLS, and the ensuing outcomes of enhanced ownership and a decrease in the probability of lethal mutations in the transformation that will invariably be undertaken by the teachers doing the actual implementations are brought to the forefront by D. Couso. Meaningful participation in a community of actors is highlighted as an important paradigm for reducing the gap between design and classroom implementation and is reified in multiple ways in the second part of the book. It is also an important mechanism for empowering teachers to manage the change that is becoming a continuous feature of school reality. In this sense, the paradigm of design-based research has the potential to engage communities in informed processes that promote meaningful and effective professional growth throughout the professional lifespan. This idea of design as a shared activity in a common space between researchers and teachers and the role of empirical evidence in guiding iterative improvements is explored in the chapter by K. Juuti and J. Lavonen.

The everyday reality of schools and teachers imposes a number of constraints on any effort for collaboration or reflective practice informed by evidence. The teaching profession requires intensive decision-making about students, approaches, contents, and learning events. Teachers as professionals grow accustomed to bringing their experience and knowledge to bear on how they act on a daily basis, sometimes with rapidly alternating student samples. It is not surprising that ensuring theoretically informed practice is not commonly very high on the priority list of teachers as part of their daily routine. Collaboration, team learning, and participation in purposeful communities that feed on distributed expertise but also produce tangible constructs, such as TLSs, with direct utility for teaching and learning provide a mechanism for addressing this challenge.

One type of decision-making that often challenges teachers in those systems with enhanced autonomy refers to curricular choices relating to contemporary science topics. **Materials Science** is quite unique from this perspective. It has emerged as an interdisciplinary domain of research that makes connections between properties, characterization, and synthesis for specific applications (chapter by

E. Hatzikraniotis and Th. Kyratsi). As part of school science, it has the potential to serve as a context for making connections between the behavior of materials under specific conditions, their properties, and their microstructure. The topic also serves as a frame for introducing the particle nature of matter and for linking phenomena with microscopic mechanisms that can provide consistent interpretations (chapter by D. Psillos, T. Molohidis, M. Kallery, and E. Hatzikraniotis). In addition, it offers an opportunity for exploring epistemic knowledge, for example, in relation to the interconnections between science and technology as, for example, in the chapters by N. Papadouris, C. Constantinou, M. Papaevripidou, M. Lividjis, A. Scholinaki, and R. Hadjilouca and Testa I., Monroy G., or the distinction between causality and explanation (A. Zoupidis, A. Spyrtou, G. Malandrakis, and P. Kariotoglou).

In the case studies presented in this book (Part III Case Studies), the authors have sought to build on this strength by developing specific TLSs whose content bears a close connection with conventional curricula but is also enriched by the multidisciplinary knowledge that has emerged in the research domain of Materials Science. On the one hand, we have the organization of educational visits to industrial sites when students can observe the application of knowledge and scientific practices in situ and can explore the involvement of individual scientists and engineers in rewarding and meaningful careers (A. Loukomies, J. Lavonen, K. Juuti, V. Meisalo, and J. Lampiselkä). On the other hand, we also have individual TLSs that explore the application of scientific principles in developing solutions to real technological problems such as the issue of acoustic insulation (chapter M. I. Hernández and R. Pintó) or the design of an electromagnetic train (N. Papadouris, C. Constantinou, M. Papaevripidou, M. Lividjis, A. Scholinaki, and R. Hadjilouca).

In all these examples, students are offered opportunities to experience firsthand the interplay between science and technology as well as the value of coherent scientific knowledge being put to the service of meeting social needs as, for example, in the chapter by A. Zoupidis, A. Spyrtou, G. Malandrakis, and P. Kariotoglou who make the case for student treatments of a real-life problem, i.e., bringing to the sea surface a ship that has sunk off the coast of an island in Greece.

Inquiry-based science education (IBSE) has been an educational policy priority for many years now (Introduction). Over the last decade, numerous interpretations of IBSE have emerged across Europe as researchers and teachers seek to connect this construct to local educational paradigms and facilitate meaningful change from where practice is currently situated. In the approaches reported in this book, it has been interesting to note that all authors have avoided a recipe-like or a procedural interpretation of IBSE. There is no reference to one inquiry cycle or to a uniform structure for developing TLSs. As a result, the design efforts have led to distinct structures for each TLS based on the needs of the corresponding content that is being elaborated by teachers and students. The modules that have been the subject of case studies in Part III Case Studies are both rich and various. It is the process of engaging students into active learning processes, including investigative and problem-solving activities, that have given the TLS the facility to promote the development of coherent conceptual models: these emerge as the main features that are characteristic of inquiry-oriented teaching and learning sequences and IBSE more broadly.

From this perspective, inquiry can be thought of as a teaching and learning framework that promotes active learning; aims at facilitating the development of scientific competencies, epistemological awareness, as well as coherent conceptual models; and can draw on principles from project- and problem-based learning to safeguard the emergence of student autonomy and lasting interest in scientific thought. Epistemologically, IBSE can be conceptualized as an intermediate construct that mediates our efforts to connect grand theories of teaching and learning with the actual processes of student and teacher interactions with natural and artificial phenomena.

In contrast, it is currently possible to witness other efforts that seek to engage students with empirical investigations or to promote some view of scientific literacy that is recognizable by students and the wider public as relevant to lifelong learning. IBSE is also sometimes used to refer to educational programs that promote hands-on activities, i.e., naturalistic observations, practical, field study, or laboratory work in science. In addition, it is also used to refer to efforts for infusing the thematic content of the science curriculum with topics that relate to more modern or topical ongoing research such as astronomy, space science, climate change, the human genome, superconductivity, or nanotechnology without any substantial shift from conventional teaching and learning approaches.

As in any evolving educational policy effort, it is understandable that there will be a degree of surface adoptions where some people continue in their conventional approaches renaming and reclassifying their efforts under new terminology. It is also predictable in complex social systems that others will reclaim the new terminology for the ideas that they have been trying to disseminate all along, no doubt in well-intentioned efforts to ride the policy and funding bandwagon to disseminate among the education communities those ideas that they consider valuable, irrespective of the actual policy priorities. If one adds to this the complexities that come from the language diversity across Europe and the diversity from the different educational traditions and cultures as well as the different established teaching paradigms and the varying stages of development in terms of monitoring learning/teaching and designing local educational policy, it is no wonder that we currently witness a babel of interpretations on IBSE. However, it is important to note that this state of affairs does tend to dilute the effectiveness even of pilot efforts to develop capacities, structures, and tools for promoting meaningful educational change and improved opportunities for deep learning that emphasizes active thinking over rote memorization, confounding these efforts with meaningless engagement in activities that might make science "more fun."

There is an even more important danger that is worth highlighting. As in the past, the frivolous use of scientific terminology to the point that IBSE, for example, is taken to mean anything that anyone might want it to mean, within a short time interval, leads to a situation that the same term cannot mean anything to anyone. If we cannot distinguish what falls under this paradigm and what does not then the paradigm ceases to have meaning, and policy making (and, unfortunately, researchers) has an incentive to coin new terminology. Epistemologically, this can be dangerous because it undermines the efforts of science education research as a discipline to promote cumulative development of reliable knowledge.

At the end of the day, societies need technologies for facilitating the development of students' abilities to develop and use their knowledge in innovative ways. This book highlights a range of approaches in domains relating to a variety of properties of materials in which the fundamental principles of IBSE have been implemented to develop TLSs through processes of participative design and iterative refinement with the use of classroom trials. Besides, in this process, several rich examples of modifications carried out in the TLS are presented and thoroughly discussed thus providing for some advancement on the rather neglected issue of modeling specific design decisions based on research evidence (chapters by A. Zoupidis, A. Spyrtou, G. Malandrakis, and P. Kariotoglou; M. I. Hernández and R. Pintó; D. Psillos, T. Molohidis, M. Kallery, and E. Hatzikraniotis; I. Testa, and G. Monroy). The extent to which these chapters highlight approaches for engaging students and their teachers in addressing meaningful questions and in developing ownership of the process of constructing meaning will have offered a rich methodological resource on which to build for future research but also to guide informed teaching practice. The book also provides interesting examples of didactic transpositions and the principles that guide informed transformations.

Perhaps its greatest value is that it brings the science education research community a step closer to identifying a coherent set of design principles for deep and lasting learning as a process of promoting scientific thinking.

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