Theoretical Issues Related to Designing and Developing Teaching-Learning Sequences

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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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