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Special Issue

Teaching–learning sequences: aims and tools for science education research

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One notable line of inquiry, aspects of which date back to the early 1980s, involves the design and implementation not of long-term curricula, but of topic-oriented sequences for teaching science. One distinguishing characteristic of a teaching–learning sequence (TLS) is its inclusion in a gradual research-based evolutionary process aiming at interlacing the scientific and the student perspective. In the present paper, which is introductory to the special issue, we attempt to serve a double purpose: on the one hand, we provide an overview of developments and trends with regard to TLSs and their classroom validation, discussing empirical studies, theoretical proposals, methodological tools and approaches to describing the design of these sequences in ordinary language, while on the other the paper serves as an introduction to this volume, making it easier for the reader to apprehend the processes of development and validation of research on TLSs.

Introduction

About teaching–learning sequences

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 notable line of inquiry, aspects of which date back to the early 1980s, involves the design and implementation not of long-term curricula, but of topic-oriented sequences for science teaching in areas like optics, heat, electricity, structure of matter, fluids, respiration and photosynthesis.

This trend falls within a science education research tradition by which teaching and learning are investigated at a micro-level (e.g. specific session) or a medium level (e.g. single topic sequence) rather than at the macro-level of a whole curriculum (one or more years) (Kariotoglou and Tselfes 2000).

One distinctive feature of such investigative activities and products is their dual character, which involves both research and development targeting a close linking of the teaching and learning of a particular topic. Teaching sequences of this kind in effect draw on the tradition of action research, being used both as research tools and as innovations aiming at the handling of specific topic-related learning problems. In science education, questions and issues regarding the character of research into teaching sequences have been brought to the attention of the European research

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community by Lijnse (1994, 1995), who argues that this sort of activity is a kind of 'developmental research' involving the interlacing of design, development and application of a teaching sequence on a specific topic, usually lasting a few weeks, in a cycling evolutionary process enlightened by rich research data. A little later, Kattman et al. (1995) presented a framework for elaborating and improving the design of teaching–learning sequences (TLSs) in terms of 'Educational Reconstruction'. It is worth noting that in mathematics education Artigue (1988) had already suggested a fruitful theoretical framework for developing teaching sequences drawing the attention to *a priori* epistemological analysis of the topic to be taught, an approach which is also fruitful for science education. These three approaches are developed later.

Although various terms have been used in the past, the term 'teaching–learning sequence' – introduced following recent international symposia – is now widely used to denote the close linkage between proposed teaching and expected student learning as a distinguishing feature of a research-inspired topic-oriented sequence (Méheut and Psillos 2000, Psillos and Méheut 2001).[1] 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.

Considerations that in one way or another seem to influence the development of such TLSs have included research into students' conceptions, features of the specific scientific domain, epistemological assumptions, learning perspectives, current pedagogical approaches and features of the educational context. Published papers often present student learning outcomes from various TLSs, which are extensively discussed by the researchers. Yet whereas there is often extensive communication of learning results, the various explicit and implicit assumptions and decisions concerning the design of a TLS, its teaching features or the interlacing of teaching with learning are less widely discussed, and may not even be made clear and comprehensible. This may perhaps be due to lack of space in journals, or it may be due to craft knowledge involved in the teaching and handling of specific content, or to a lack of widely accepted tools for representing teaching, a situation that warrants further study (Fensham 2001). This is the context in which we envisioned this special issue, following the organization of international meetings on the same theme (see note). In the present introductory paper we attempt to serve a double purpose: on the one hand, we provide an overview of developments and trends with regard to TLSs and their classroom validation, discussing empirical studies, theoretical proposals, methodological tools and approaches to describing the design of these sequences in ordinary language; while on the other hand, the paper serves as an introduction to this volume, making it easier for the reader to apprehend the processes of development and validation of research on TLSs.

A classification scheme

One distinguishing characteristic of a TLS is its inclusion in a gradual research-based evolutionary process aiming at interlacing the scientific and the student perspective. In the present paper we attempt to discuss and bring together two of the steps involved in experimenting with a TLS, namely design and validation. Our sample consists of several sequences published in various countries, although we do

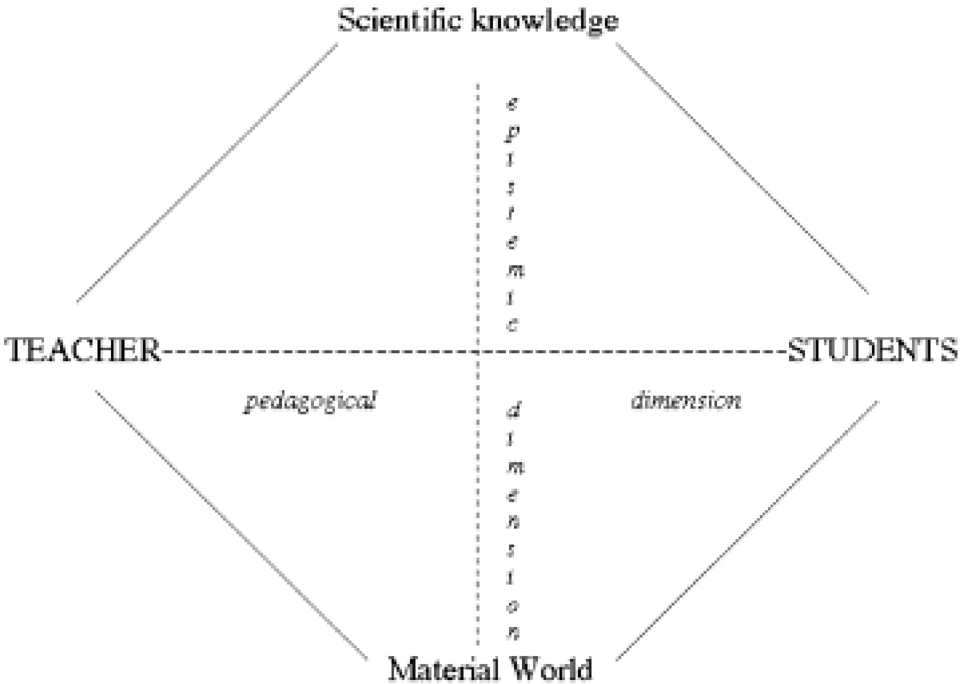

Figure 1. The didactical rhombus.

not claim to cover the field comprehensively. We endeavour to reveal certain trends, drawing on different research traditions, from both well-known and less familiar publications, so as to enrich the public discussion on TLSs. Some TLS studies, surprisingly, seem largely unaware of others with which they share common perspectives and assumptions. In this *a posteriori* classification, we use the recently suggested term 'teaching–learning sequence' across the board, regardless of the terms originally used by the various authors. In doing so we are cognizant of the fact that certain of the studies reviewed involve aspects of TLSs focusing on different levels: for example, some studies may deal with the micro-level of a few tasks within a sequence while others provide overall treatment of an entire sequence.

On the first point, that of design, we will focus on the main considerations put into play when designing a TLS as these emerge, implicitly or explicitly, from several studies. The discussion will focus on issues like the design of teaching–learning situations, problems, activities, the part played in decisions by a variety of considerations including content analysis, epistemology, students' conceptions and motivations, learning and pedagogical theories and educational constraints. We try to organize this diffuse mass of considerations using a two-axis 'didactical rhombus' as presented in figure 1. In this schema, the vertical axis represents the 'epistemic' dimension (i.e. how knowledge works with respect to the material world) and the horizontal axis the 'pedagogical' dimension (i.e. the choices about the respective parts to be played by teacher and class).

Along the epistemic axis, for example, we find assumptions about scientific methods, the processes of elaboration and validation of scientific knowledge that underlie the design of the sequence. Along the pedagogical axis, we will find choices about the teacher's role, types of interaction between teacher and students and, close to the 'Students' vertex, interactions between students. Along the 'Students–Material World' side we will place students' conceptions of physical phenomena, with more general spontaneous ways of reasoning closer to the 'Students' vertex. Students' attitudes towards scientific knowledge will be placed along the 'Students–Scientific Knowledge' side.

This pictorial representation permits the organization of the various considerations put into play during the process of designing a TLS, and indicates the relative independence of the epistemic and pedagogical dimensions. Combining the two dimensions tells us more about the interplay between the epistemological and the pedagogical components of the design of a TLS. Our review points out that some studies emphasize the pedagogical dimension, others the epistemic dimension, while in a third group the dimensions are interlaced. Researchers generally do not specify how they take into account contextual factors, notably educational constraints, apart from some typical descriptive information. So we will focus this review on the epistemic and pedagogical dimensions and not include contextual factors in this analysis.

In the second part of the paper, we will focus on various possible approaches to the validation of such TLSs. The focus will be on the extent to which the research methodology permits evaluation of the effectiveness of the sequence with regard to specific objectives, and on the validation of the choices or hypotheses underlying the design of activities. We will see that two main points of view can be outlined. The first can be seen as resembling 'production engineering': it is mainly expressed in terms of the feasibility and/or effectiveness of a global teaching–learning package. The second is more like 'experimental research', with an approach that is more analytical in terms of describing learning pathways and validating hypotheses. We will discuss whether these two approaches can be developed in a complementary manner.

Designing TLSs: some trends

It seems that we may encounter some difficulties in reconstructing the historical development of research on TLSs, perhaps because in the early steps of the development of science education research attention was focused on students' conceptions and ways of reasoning. It may be that some less student-centred points of view were difficult to publish and have remained more confidential, their diffusion limited. We will, however, try to characterize some interesting trends and to situate these trends with respect to our didactical rhombus.

A psychological constructivism?

During the 1970s and early 1980s, the accent was on research into the (mis)conceptions, representations and spontaneous reasoning of the learner. The question naturally arose as to how to take such pieces of information into account in order to improve science teaching and learning. One current, which resulted in research-based teaching approaches, was strongly 'learner-centred', emphasizing the students' resources and the potentialities of confronting their ways of reasoning with data from the material world (Driver and Oldham 1986).

Such approaches could be situated on our didactical rhombus in proximity to the 'Students–Material World' side, the attention paid to the teacher's role being limited and the epistemic point of view poorly developed.

Comprehensive reviews of the considerable amount of research work developed in this perspective can be found, for example, in Scott et al. (1992) and in Duit (1999).

Answers to the question already expressed range from the radical constructivist to the moderate. In the radical responses, the teacher's role is mainly to establish a favourable climate for student discussions and activities, the students being largely responsible for formulating and solving problems themselves. This point of view is expressed by Von Glasersfeld:

> The teacher's art [. . .] resides in getting students to generate problems of their own that are conducive to the ways of thinking that are to be taught. (1992: 37)

It also appears in problem-posing approaches:

> In other words: preferably the students themselves should pose the problem to be further investigated [. . .] they themselves frame the questions that drive their learning processes. (Kortland 2001: 9–10)

This type of model focuses closely on the students, and on the role of the teacher as a facilitator of student activities. Major choices underlying the design of the sequence are independent of the specific domain of scientific knowledge.

In less radical approaches, the teacher (or researcher) is in charge of elaborating the problems to be solved; as we will see, this can lean more towards psychological justification or epistemological argument. Here, we consider one main approach that gives great importance to contradictions. A first set of research work (see, for instance, Dewey and Dykstra 1992, Driver and Bell 1986, Driver and Erickson 1983, Nussbaum 1989, Nussbaum and Novick 1982, Ravanis and Papamichael 1995) puts the accent on clarification of pupils' ideas when interpreting or predicting the results of experiments and 'destabilization' of these incorrect ideas when confronted with contradictory observation. Other authors use the word 'conflict' to describe the contradictions between individual pupils' different thought processes (Rebmann and Bugeat 1994, Stavy and Berkovitz 1980). Another source of conflict can be found in the contradictions between the thought-processes of different pupils (Champagne et al. 1985).

Let us note that, restricting ourselves to the didactics of physics and chemistry, it is difficult to evaluate the advantages and limits of such 'conflict' strategies. If some studies conclude the effectiveness of such strategies (Guzetti et al. 1993), this conclusion is not fully shared. Nussbaum (1989) questions these teaching strategies, stating that 'the students maintain substantial elements of the old conceptions' (p. 538), while Schwedes and Schmidt (1992) and Scott et al. (1992) go a step further, questioning the way in which pupils recognize these programmed 'conflicts' and how they resolve them (Chinn and Brewer 1993). These researchers touch upon two important issues. The first is that what researchers consider a 'conflict situation' is not necessarily such for the students, at least with regard to experiments. Examples from teaching electricity are illuminating in this respect (Koumaras et al. 1997, Psillos et al. 1987). The second issue is that, in a number of cases, the data gathered tend to assess the global effectiveness of a teaching sequence rather than permit precise analysis of the setting up and development of a specific conflict (see later). Although the high expectations of conflict strategies were not fulfilled, appropriate embedding of conflict situations in a TLS may improve its effectiveness.

An epistemic constructivism?

Another current of research-inspired approaches to science teaching tilted strongly towards what our framework describes as the epistemic point of view. We will outline certain of these approaches, which are mainly argued with respect to the scientific content to be developed rather than with respect to students and teachers.

Various aspects of scientific knowledge can be used as a driving force for the learning process. Some approaches rely on the use of analogies between different fields of knowledge: such TLSs have been developed in particular in the field of electro-kinetics, using hydraulic (Schwedes and Dudeck 1996, Schwedes and Schmidt 1992) and thermal (Dupin and Johsua 1993) analogies.

Others rest on analysis of pieces of knowledge as tools for solving problems. Such approaches enhance the relationship between the problems and the knowledge that provides answers to them. Students are expected to develop, or at least appropriate, new knowledge by solving well-designed problems (e.g. prediction problems), the underlying idea again being to highlight the limits of available thought-processes and to favour the elaboration or appropriation of new knowledge.

It seems that such approaches have not yielded many international publications, which may explain why some authors feel that little attention is paid to science content in contemporary research in science education (Fensham 2001, Lijnse 1995). We will illustrate this approach here with a few examples found in national and international literature originating from France. Tsoumpelis (1993) envisages building up the notion of molar concentration through prediction problems on differences in osmotic level by varying different factors. In mechanics, in a sequence studying free fall, Robardet (1995) asks for predictions relative to the falling movements of two objects of different mass; the rest of the sequence is structured by the search for a relationship between the speeds of the falling object at different moments in time. This type of problem (the search for a relationship between different concepts) has been studied by Weil-Barais and Lemeignan (1990) concerning the quantity-of-movement concept. These same authors (Lemeignan and Weil-Barais 1994) also propose training activities in the concept of energy by setting up energy-transformation chains: making a bulb last longer and give a stronger light or a small car go faster and farther by the use of a battery, a hair-dryer, a pressure-cooker, the sun, and so on. Supplementing these action problems (production of such and such an effect) are representation activities aiming at describing the way the devices function in terms of energy transfer.

So, alongside prediction problems (which are at the heart of research into 'cognitive conflicts'), other types of problems can also be used as driving forces for learning; for example, action problems on material systems (producing, modifying an effect), or more 'theoretical' problems, such as how to establish a relationship between physical quantities or how to represent different phenomena in a unifying manner. Such approaches can be linked to an instrumentalist view of science, the aims of scientific activity being not so much the verification (or refutation) of theory, but rather the elaboration of ever more powerful models. From this modelling point of view, problems are useful not only to solve contradictions, but also to develop models as simple and powerful as possible, in order to explain seemingly different phenomena in a unifying manner and to support action and prediction.

As mentioned earlier, such approaches could be situated on our didactical rhombus very close to the vertical axis: the driving forces of learning are sought from the epistemic significance of knowledge. It is more or less implicitly supposed that such epistemic driving forces can act as forces driving learning.

Towards an integrated constructivism?

These two registers – that is, the psycho-cognitive and the epistemological – were already apparent in the early 1980s. In such early approaches, the choice of experiments (and of questions) is based on analysis of the pupils' preliminary knowledge. The aims of instruction are purposely limited; the 'notions' taught are placed in relation to the scientific concepts they prefigure. This double reference – to the pupils' knowledge and their conceptions about the physical world on the one hand, and to scientific knowledge on the other – allows researchers to propose original steps in the conceptualization of the phenomena, which may not always coincide with those included in textbooks or curricula. For example, in a study on teaching notions of temperature and heat, Tiberghien and Barboux (1983), among others, propose manipulations to lead the pupils to establish a 'link between the temperature of a substance and the thermal balance of its environment' (p. 7) and to generalize to all substances 'the increase in temperature when heated (excepting change of state)' (p. 7). The knowledge to be attained here, very simple at first sight, in reality represents a major step for the pupils in relation to their prior conceptions: in fact, it seems that pupils, before being taught this, think that the temperature of certain substances (ice and sand, for example) is not subject to variation. Similarly, Séré and Chomat (1983) questioned their representation of a gaseous state and suggested learning situations in which the objectives are that pupils give certain substance properties to the gases, particularly concerning weight and the conservation of quantity during different transformations.

Such studies marked an important step in the conception of TLSs, with the initial cognitive state of students being defined as far as is covered by current research, and the desired final cognitive state being defined according to scientific knowledge, which is transformed so as to adapt to students' reasoning. While this gave only a partial response to the characterization of the pedagogical process towards achievement of this final state, we may nonetheless note the importance given to the setting up of manipulations 'favourable to the pupils' expression of conceptions and their evolution' (Tiberghien and Barboux 1983: 5).

We find a similar approach in more recent work, where the focus is both on the pupil and on characterization of the knowledge in question. In these studies the scientific content is considered problematic, and is handled by the researchers in such a way as to give rise to innovative representations of scientific concepts and their relations according to the aims of instruction as perceived by the researcher.

Thus the notion of pressure at junior high school level is introduced as a primary concept in a constructivist sequence on fluids. Force is introduced later on, and the pupils are expected to establish the relation force/pressure after differentiating between force and pressure (Kariotoglou et al. 1995, Psillos and Kariotoglou 1999). In another study, voltage is introduced as a primary concept in a sequence on electric circuits at junior high school level, whereas current intensity is generally the introductory primary concept in school curricula (Psillos et al. 1988; Tiberghien et al. 1995). Differentiation of the concepts of intensity, tension and energy is a prominent objective of this sequence, in which the experimental field includes the duration of a battery, unlike the usual pattern where only brightness is treated. In another sequence on introductory electricity, Barbas and Psillos used transient states of electrical circuits in order to compensate for the observed dissociation of electrostatic and electro-kinetic phenomena by the students, taking into account their causal thinking as well (Barbas and Psillos 1997)

Several other examples may be also cited, concerning traditional topics like optics (Chauvet 1996, Galili 1996, Kaminski 1991) at junior high school level, energy (Trumper 1990), structure of matter and particle models (Méheut 1997, Méheut and Chomat 1990, Scott 1992, Vollebreght 1998) or, more recently, superposition principle (Viennot and Rainson 1999), and modern topics like non-linear physics in upper school physics classes (Komorek et al. 2001), fuzzy topics like the introductory treatment of errors at university level (Evangelinos et al. 2002) or cross-discipline ones like tides (Viiri and Saari 2004).

We may observe that some of these approaches give a significant role to contradiction as a source of motivation for learning, while others are more explicitly modelling-oriented (Gilbert and Boulter 1998). We can see here an expression of different epistemological points of view; one more logical, the other more instrumentalist.

Among the numerous studies on the use of analogies (see, for example, Arnold and Millar 1996, Duit 1991, Glynn 1991), we find some that are mainly knowledge-centred, resting on an analysis of similarities between domains, and others that are more integrated, taking into account both psycho-cognitive data about the students and epistemic analysis about the analogical structures of the knowledge in question. Bridging analogy strategies can also be considered as belonging to this type of integrated constructivist approach (Brown 1994).

Such approaches may be located on our didactical rhombus to the right of the vertical axis, interlacing considerations about the students, their relation to material world, and epistemic points of view.

One important remark about these and previous studies is that they pay little attention to the role of the teacher. Let us remark that recent pieces of research work, in a Vygotskian approach, plead for more attention to be given to this aspect (Dumas-Carré and Weil-Barais 1998, Leach and Scott 2002).

Validating TLSs: some trends

If we look at the utilization of a sequence as a teaching and/or research tool, various kinds of validation appear. Some methodological approaches aim at evaluating the effectiveness of a sequence by comparing the students' cognitive 'final state' with their cognitive 'initial state'. Other approaches illuminate students' cognitive pathways all through the teaching–learning process.

Pre-test/post-test procedures

The methodology often adopted tends to prove the effectiveness of a teaching package in relation to specific learning objectives. Data can be collected in the form of tests carried out after the sequence. The effectiveness of such an approach can be found by comparing these results with those obtained by the same pupils before the sequence (sometimes called 'internal' evaluation) or by those of a group of pupils judged to be of the same level and who have not attended the same sequence (sometimes called 'external' evaluation). The first objectives of internal evaluations are to test the effectiveness of the sequence in relation to the initial objectives (see, for example, Andersson and Bach 1996, Asoko 1996, Boohan 1996, Mortimer 1993, Thiis 1992). 'External' evaluations allow us to ascertain that, in relation to our objectives, work done together with the pupils is more effective than other types of teaching taken as reference (see, for example, Chang and Barufaldi 1999, Kariotoglou et al. 1995, Minstrell 1992, Nikolopoulou 1993, Psillos 1998, Ravanis and Papamichael 1995).

Internal or external evaluations have also been used to characterize the relative difficulty of a given objective. Thus, Tiberghien and Barboux (1983) concluded, after such a sequence, that the notion of thermal equilibrium is difficult to acquire in the junior secondary school years, although the fact that the temperature does not vary when there is a change of state proves to be less of a problem. Later, Chauvet tried to characterize the 'obstacles and persistent difficulties' at the end of a teaching sequence on colour, 'persistence of the common conception of colour as matter' and 'fragility of the conceptualisation of coloured light' (1994: 179). Conceptual profiles can be considered as fruitful evaluation tools in this perspective (Viennot and Rainson 1999).

Such types of evaluation generate the following questions.

- Some cognitive objectives prove to be easy or difficult to reach, but can such results be considered as general and independent of the conditions in which they have been obtained?
- Which choices in the design of the learning situations are determinant for the effectiveness of the learning process? In the gap between usual types of teaching and experimental teaching, what actually makes the difference?

Here we encounter problems relating to the control of variables and the reproducibility of experimental teaching. If these questions have been the object of didactical studies in mathematics (Artigue 1984, Brousseau 1981), it seems that they are latent in the didactics of physics and chemistry. In the past few years they have appeared in declarative rather than operational form in international publications in the didactics of physics. Thus, Hewson and Thorley (1989) remark that if the model of 'conceptual change' has been set in motion in numerous teaching sequences, the data thus gathered were insufficient to permit discussion of the role played by the specific factors considered as essential in putting this model into effect. The precautions taken by certain authors in presenting their conclusions show that they share these preoccupations. Thus, Johsua and Dupin (1989: 201) bet on the reproducibility of their observations, whereas Rainson (1995: 152) leaves the issue open. Andersson and Bach (1996) formulate the problem clearly in relation to their own experiments:

> There is, however, one question that the improved design does not answer. Which aspects of the teaching were particularly important, and which were less important, with reference to achieving the observed result? (p. 18)

Studying learning pathways

Another type of approach that has gained prominence in science education research consists of observing pupils all through the learning process. This seems indispensable if we want the study of the learning processes to be focused and to test the choices made in the elaboration of specific teaching–learning situations.

We can find this preoccupation in some early studies (see, for example, Méheut 1982, Séré 1985, Tiberghien and Barboux 1983) that included observations, collected as manipulation memos and written answers to teachers' questions or tests. Such an initial preoccupation is further elaborated in more recent works in terms of the description of cognitive itineraries, conceptual pathways or learning pathways (see, for example, Arnold and Millar 1996, Aufschnaiter and Welzel 1999, Duit et al. 1992: part 3, Galili 1996, Niedderer 1997, Petri and Niedderer 1998, Psillos and Kariotoglou 1999, Welzel 1998).

Detailed analyses of students' learning pathways can be used to discuss the effectiveness of a specific learning situation, in addition to the overall evaluation of a sequence, to test hypotheses underlying the design of the learning situations and to improve them. For example, a detailed analysis of a student's learning pathway allows Schwedes and Schmidt (1992) to discuss the reality of expected cognitive conflicts and to bring to light some unexpected difficulties encountered in developing an analogy between hydraulic and electric circuits; Psillos and Kariotoglou (1999) traced the various learning pathways of students who were engaged in a teaching sequence in fluids, and thus accounted for their differential reaction to a conflict situation. We find similar kinds of results in Arnold and Millar (1996), regarding the use of an analogy in the teaching of heat, temperature and thermal equilibrium, and in Duit et al. (1998), regarding the use of an analogy in a unit on chaotic systems.

As we will see further, such research presents some characteristics of what Lijnse (1994) defined as 'developmental research': data analysis makes it possible to discuss and improve the effectiveness of teaching–learning strategies – see, for instance, the evolution of strategies between Schwedes and Schmidt (1992) and Schwedes and Dudeck (1996).

Collecting the contributions of various theoretical and methodological frameworks

In the previous paragraphs we have tried to illustrate some trends in the development of specific TLSs and ways of validating them that have been used in several studies. In addition to a number of topic-oriented sequences, an important development in this field is the public presentation of general frameworks focusing on the factors taken into account and processes involved in designing sequences as a research activity. We now outline some of these general frameworks, which probably reflect different research traditions and educational contexts, in order to illustrate their specific contributions in the discussion on TLSs as well as their possible common points or differences.

About 'Developmental Research'

General issues concerning the place of TLSs in science education research were brought to the fore in the area of European physics education with Piet Lijnse's papers on 'developmental research' (Lijnse 1994, 1995). Surprisingly, or perhaps unaware of some still barely perceptible research currents (see earlier), he talks of 'the almost complete lack of attention to science content' in contemporary research in science education. He also doubts whether general learning or pedagogical theories may prove useful when it comes to the level of specific topic-oriented designs. In order to 'fill the gap between theory and practice', Lijnse proposed a general schema for developing 'didactical structures'. Starting from Freudenthal's position, Lijnse attaches great importance to the freedom of students to follow their own elaborations. He considers that 'conceptual change' and, particularly, 'cognitive-conflict' strategies do not give students this opportunity. The problem is then formulated as 'to conceive teaching situations to lead students to build freely the ideas we want to teach them'.

Lijnse proposes some guidelines for designing such teaching–learning situations. In these guidelines, 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. Referring to this framework, Kortland (2001) proposes to deconstruct the teaching–learning process into five phases: motivation, question, investigation, application and reflection.

Piet Lijnse gives great importance to empiric regulation in the process of elaborating 'didactical structures'. Such regulation starts from a scenario describing and justifying (*a priori*) the design of teaching–learning activities and the expected teaching–learning processes. The teacher can use such a scenario when preparing the classroom trial, and it is also a guide for classroom observations in the perspective of producing didactical structures 'good enough for teaching practice'.

About 'Educational Reconstruction'

The model of 'educational reconstruction' developed by Kattmann et al. (1995) provides a framework for designing and validating TLSs that draws on planning instruction models that were developed in the German pedagogical tradition. The model attempts to combine the German hermeneutic tradition on scientific content with constructivist approaches to teaching and learning. It holds that clarification of science subject matter is a key issue if instruction in particular science content is to be developed. This is a process called 'elementarization', which leads to constructing the core ('elementary') ideas of the content to be taught. Often this clarification process is primarily or solely informed by issues coming from the structure of the referent science content. Educational issues are then regarded only after the science subject matter has been clarified. The significant feature of the educational reconstruction approach is that its analysis of science content takes into account not only epistemic dimensions (genesis, function and meaning of the concepts), but also context, applications and ethical and social implications.

The educational reconstruction model closely links considerations on the science concept structure with analyses of the educational significance of the content in question and with empirical studies on students' learning processes and interests. Students' conceptions are taken into account in a constructive perspective in reconstructing science content structure by providing answers to questions like

'Which are the most relevant elements of the students' conceptual framework to be respected? Which opportunities are opened by certain elements of students' conceptions or perspectives? Which conceptions of students correspond with scientific concepts in such a way that they can be used for a more adequate and fruitful learning?' (Kattmann et al. 1995).

The 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 material setting, while science knowledge, on the other, is viewed as a tentative human construction. Results of the analysis of content structure (linking clarification of the core concepts and analysis of the educational significance) 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, elementarization, and even the setting of detailed goals and objectives. This procedure is rather unusual for educational research, yet it fits the situation that a particular content structure for instruction has to be developed according to the students' point of view, and especially according to their pre-instructional conceptions and their learning paths. The science content structure and the students' conceptions and frames of interpretation are seen as being equally important parameters in the process of educational reconstruction and are necessary for the achievement of the goals of science teaching. A special characteristic of the model is that knowledge gained in one of the components influences the activities and the interpretation of the results of the other components in a dynamic process.

About 'Ingénierie Didactique'

Another framework that was developed in mathematics education research is, as we mentioned earlier, also useful for science education. This framework proposed guidelines for both designing and validating a sequence. In this general framework, Artigue (1988) suggested 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 interlaced in order to accurately define 'problems' to be managed by students and to anticipate the elaboration of knowledge by students through these 'problems'. The comparison of the cognitive itineraries actually observed with those predicted can validate or challenge the hypotheses involved in the building up of learning situations.

Designing a TLS

We may situate the features of these three frameworks with the help of our didactical rhombus: students, material world, scientific knowledge, teacher.

In the framework of developmental research, Lijnse (1994, 1995) focuses mainly on students and only secondarily on the role of the teacher; the epistemic dimensions of the knowledge to be taught are not evoked as playing a determining part in planning the didactical structure; problems are to be formulated by the students, with the help of the teacher; only general indications about a progression are given by the researchers.

Both 'Ingénierie Didactique' (Artigue 1988) and 'Educational Reconstruction' (Kattmann et al. 1995) suggest precise guidelines with regard to the epistemic dimension. In 'Ingénierie Didactique' the elaboration of problems to be treated is the responsibility of the researchers, and is strongly linked to content analysis. As already mentioned, Artigue focuses on *a priori* analyses: epistemological, psycho-cognitive (conceptions and reasoning), and 'didactic' (educational constraints), while little is said about the psycho-affective and social aspects of teaching–learning processes. In 'Educational Reconstruction' we can also find content and psycho-cognitive analysis, as well as much about motivation and the social and ethic implications of the knowledge to be taught, but little discussion of educational constraints.

Thus, the developmental research framework appears to be more psychologically based, and the design of activities student-centred, whereas in 'Ingénierie Didactique' epistemic points of view appear more explicit. 'Educational Reconstruction' can appear as taking into account quite explicitly psycho-social points of view and epistemic analyses and their interlacing. We note that our remarks reflect what the authors say about the relative emphases in their frameworks, and do not imply that other aspects are ignored.

We may note that certain features are common to all the theoretical proposals and empirical studies: on the one hand, the treatment of the usual scientific content as problematic in relation to the aims of instruction as perceived by the designers, and on the other the dynamic character of the development of a TLS, the features of which are further discussed in the next section. This means that designing a TLS is not a 'one-shot' activity, but a long-term endeavour, one product of which is often an innovative content representation, which is different from those appearing in numerous textbooks and curricula worldwide.

With regard to empirical research, we note that some factors could or should be more explicitly taken into consideration in the design of a TLS. This is the case with educational constraints, which are rarely explicitly managed or even reported (Tiberghien 1996). In other words we argue that researchers should make public the craft handling of contextual factors and particularly educational constraints. We believe that this is a difficult endeavour bearing on the feasibility of TLS 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 (Dumas-Carré and Weil-Barais 1998, Leach and Scott 2002).

We consider that the features and processes that one researcher may take into account in designing his/her TLS may vary according to personal preferences and contexts. However, we suggest that a challenge for the future in this field is clarification of the assumptions, or even distinction of the frames, that are taken into account in designing a TLS. In other words, we plead for more 'frame-based' research and development on TLSs.

Validating a TLS

We discuss here certain perspectives concerning empirical regulation in the process of elaborating a TLS. As pointed out all through this paper, empirical regulation is intimately related to developing a TLS. From both the theoretical frameworks and the empirical studies there emerges a long-term design, remote from a 'one-shot' endeavour, that may involve different foci of validation, either between the various TLS or between successive trials within a TLS.

From the 'Developmental Research' and 'Ingénierie Didactique' frameworks we will retain the notion of a teaching–learning scenario and the idea of comparing students' actual cognitive pathways with anticipated ones. Such a comparison makes possible an effective empiric regulation procedure, aimed at reducing the observed deviations from the expected evolution undergone by the students; it can also provide opportunities for the validation, or refutation, of certain precise hypotheses underlying the design of a TLS and/or specific situations included within it. In other words, a scenario may be a useful tool for checking the validity of 'local' hypotheses within the context of a global TLS.

In the perspective of 'Developmental Research', the results of experimenting with a TLS can be seen as 'adequate didactical structures', 'good enough teaching–learning processes', and so on. Strong emphasis is put on empirical regulation of the process of producing such didactical structures. In the perspective of 'Ingénierie Didactique', the emphasis is on validating or challenging hypotheses involved in the building up of didactical situations by comparing the students' actual cognitive pathways to anticipated ones.

We argue that it is fruitful to situate these two perspectives with regard to two main methodological paradigms for using TLS in a research perspective, the first more 'production engineering' oriented and the other leaning more towards 'experimental research'. We will try to demonstrate how complementary they can be. Demonstrating the feasibility or effectiveness of a sequence can be linked to the pragmatic perspective of developing 'good educational products'. Trying to achieve precise descriptions of students' cognitive pathways and to test certain specific hypotheses can be linked to a perspective of understanding cognitive processes and testing learning theories. In order to make the distinction clear, we can also think about the following assertions: 'A sequence can be very effective without our really knowing why' . . . or . . . 'A sequence can be less effective but experimenting allows us to know why'. . . or . . . the best . . . 'A sequence can be very effective and we know precisely why'. So experimenting with a TLS can lead to two types of interesting results: results in terms of pragmatic value (feasibility, effectiveness, etc.) and/or results in terms of scientific validity (understanding learning processes, testing learning theories, etc.).

We consider that, for some researchers, the aims of experimenting with a TLS can be more on the 'production engineering' side and, for others, on the 'experimental research' side (Méheut 2001). We suggest that these are not contradictory, and can be attempted within a single piece of research. In our opinion, to make such aims 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 research today. It would allow researchers to answer both the requirements we face: that of pragmatic value and that of scientific validity. We hope that this special issue will contribute significantly to this project.

Presentation of the contributions to this special issue

The six papers that constitute this special volume (apart from this introductory review) can be seen as covering a wide range of themes and illustrating different research positions with regard to the issues discussed in this paper.

The TLS that are presented or discussed by the authors refer to various domains of scientific knowledge in a variety of educational contexts involving lower and upper secondary and university students. The topics are typical subjects like structure of matter (Lijnse, Klaassen and Méheut), fluids (Psillos, Tselfes and Kariotoglou), optics and conductivity (Buty, Tiberghien and Le Maréchal), solubility (Kabapínar, Leach and Scott), changes of state and the thermo-elastic properties of gases (Méheut), important new phenomena like non-linear systems (Komorek and Duit) and new issues related to scientific literacy (Linjse and Klaassen).

The papers focus on the discussion of issues related to theoretical frameworks like developmental research (Linjse and Klaassen), suggestion of new theory-based tools for the design and analysis of TLSs at the macro-level and micro-level (Buty, Tiberghien and Maréchal), modelling the didactical activities of already developed TLSs (Psillos, Tselfes and Kariotoglou), retrospective discussion of the development of TLSs in the light of theoretical frameworks (Méheut), new research methods (Komorek and Duit) and discussion of the feasibility of innovations (Kabapínar, Leach and Scott). It is notable that in several of the papers the researchers discuss existing TLSs, developed progressively by themselves and their colleagues, from new theoretical perspectives. We consider such *a posteriori* discussions as an important step towards the modelling of craft knowledge involved in the design and development of various TLSs, which may lead to a more theory-based research in the future.

Linjse and Klaassen describe 'didactical structures' as a possible outcome of research on TLSs. Starting from an explicit didactical perspective, known as the problem-posing approach, the research emphasis lies on the didactical quality with which this particular perspective can be put into classroom practice in the teaching and learning of a certain topic. They present three didactical structures elaborated according to a problem-posing approach in the general perspective of developmental research, in which a research scenario, as a detailed prediction and theoretical justification of the hypothesized teaching–learning process, plays a crucial role.

Psillos, Kariotoglou and Tselfes propose a theoretical framework for an epistemological modelling of teaching–learning activities that draws on recent studies of scientific practice. This framework is built on three categories: namely, Cosmos–Evidence–Ideas. They apply this framework to model *a posteriori* the didactical activities included in three successive TLSs in the field of fluids, developed gradually by the same researchers over several years under a sequence of evolving dominant approaches to science teaching and learning (transmission, discovery, constructivist).

Buty, Tiberghien and Le Maréchal present a tool elaborated from a theoretical framework linking epistemological, learning and didactical hypotheses. This framework leads to the design of teaching sequences from a socio-constructivist perspective and is based on the role of models in physics or chemistry and on the role of students' initial knowledge in the learning process. This tool is then applied to examples in physics and chemistry.

Méheut presents a retrospective analysis of two TLSs on particle models, describing the design process for each sequence. The development and evaluation of the two sequences are discussed with respect to general frameworks for developing TLSs such as Ingénierie Didactique and Educational Reconstruction, which provides an opportunity to clarify the similarities and differences between these two frameworks.

Komorek and Duit explore the educational potential of non-linear systems in the perspective of the Educational Reconstruction framework, which, *inter alia*, closely links analytical and empirical educational research with the development of teaching and learning sequences. In the present paper the focus is on a teaching experiment that has proven to be a valuable research method for investigating teaching and learning processes. Teaching experiments may be viewed as Piagetian critical interviews that are deliberately employed as teaching and learning situations. This method thus appears to be well suited for linking research and development in the first steps of designing teaching and learning sequences.

Kabapínar, Leach and Scott report on a study addressing the teaching and learning of the concept of dissolving at the secondary school level. The principal aim of the research was to investigate the feasibility of introducing a simple particle model of matter that students could use to make sense of the macroscopic and quantitative aspects of dissolving, thereby improving their understanding of the matter. A teaching intervention to fit within the existing chemistry curriculum was designed, which explained macroscopic and quantitative aspects of solubility in terms of particles by referring to a simple particle model of matter. To this extent, at least, the teaching intervention met the requirements and restrictions of the existing curriculum in Turkey. Findings suggest that while it is possible to design a teaching sequence that introduces a simple particle model of matter in such a way that students can successfully use it to explain various solubility phenomena, experimental subjects did not significantly outperform others, who did not follow it, in all aspects of the conceptual domain. The paper concludes with a brief discussion of the kinds of claims that can be supported from a study such as this.

Considering the elaboration of contents and the design of activities in these papers, we can see the importance given, on the one hand, to content analysis, with the help of epistemology, and on the other to students' conceptions, common-sense reasoning and motivation – the one or the other dimension being more or less developed in the various papers. Thus, we find interesting contributions about the part that epistemological considerations can play in the design of a sequence in the papers presented by Buty et al., Psillos et al. and Méheut. In these three papers, the knowledge to be taught is analysed from a 'modelling' point of view. The sequences presented by Méheut aim at helping students conceptualize a two-level world, distinguishing and discussing links between macroscopic phenomena and microscopic models; Buty et al. also use a two-level scheme ('material world/theories and models'), while Psillos et al. propose a three-level scheme ('Cosmos–Evidence–Ideas'). It is important to note that in all these papers the authors take into consideration the results of research concerning student learning difficulties, common-sense conceptions and ways of reasoning.

Another issue emerging from such a confrontation of experiences concerns ways of validating a TLS. We find real diversity here, both between the aims and between the types of data and techniques for observing the 'effects' of a sequence. The point of view developed by Kabapínar et al. in their paper is mainly focused on the feasibility and effectiveness of the sequence with respect to students' performance. In her paper, Méheut attempts to make clear two different ways of validating a sequence. The first, and perhaps the commonest, aims at proving the effectiveness of a sequence with respect to definite objectives; the other, less usual approach, is to observe and to describe the cognitive pathways of students through the activities composing the sequence. In a similar perspective, Duit treats the validity of teaching experiments as a means of investigating teaching and learning processes in the domain of chaotic systems. In these cases, data are collected during small group (from two to four or five students) working sessions, with or without an interviewer.

Note

1. An International Symposium and a Workshop on TLSs recently took place. Several of the papers appearing in this volume were presented and discussed in an initial form during these meetings. The first took place in Paris (Méheut and Psillos 2000) and the second during ESERA 2001 (Psillos and Méheut 2001).

References

ANDERSSON, B. and BACH, F. (1996) Developing new teaching sequences in science: the example of 'Gases and their properties'. In G. Welford, J. Osborne & P. Scott (eds.) *Research in Science Education in Europe: Current Issues and Themes* (London: The Falmer Press), 7–21.

ARNOLD, M. and MILLAR, R. (1996) Learning the scientific 'story': a case study in the teaching and learning of elementary thermodynamics. *Science Education*, 80(3), 249–281.

ARTIGUE, M. (1984) *Contribution à l'étude de la reproducabilité des situation didactiques*. Unpublished thesis, Université de Paris.

ARTIGUE, M. (1988) Ingéniérie didactique. *Recherches en didactique des Mathématiques*, 9(3), 281–308.

ASOKO, H. (1996) Developing scientific concepts in the primary classroom: teaching about electric circuits. In G. Welford, J. Osborne & P. Scott (eds.) *Research in Science Education in Europe: Current Issues and Themes* (London: The Falmer Press), 36–49.

AUFSCHNAITER, S. and WELZEL, M. (1999) Individual learning processes: a research programme with focus on the complexity of situated cognition. In M. Bandiera, S. Caravita, E. Torracca and M. Vicentini (eds.) *Research in Science Education in Europe* (Dordrecht: Kluwer Academic Publishers), 209–215.

BARBAS, A. and PSILLOS, D. (1997) Causal reasoning as a base for advancing a systemic approach to simple electrical circuits. *Research in Science Education*, 27(3), 445–459.

BOOHAN, R. (1996) Using a picture language to teach about processes of change. In G. Welford, J. Osborne and P. Scott (eds.) *Research in Science Education in Europe: Current Issues and Themes* (London: The Falmer Press), 85–99.

BROUSSEAU, G. (1981) Problèmes de didactique des décimaux. *Recherches en Didactique des Mathématiques*, 2–3, 37–127.

BROWN, E. D. (1994) Facilitating conceptual change using analogies and explanatory models, *International Journal of Science Education*, 16(2), 201–214.

CHAMPAGNE, A.-B., GUNSTONE, R.-F. and KLOPFER, L.-E. (1985) Effecting changes in cognitive structures among physics students. In L. West and A. Pines (eds.) *Cognitive Structure and Conceptual Change* (Orlando: Academic Press).

CHANG, C.-Y. and BARUFALDI, J.-P. (1999) The use of a problem-solving-based instructional model in initiating change in students' achievement and alternative frameworks. *International Journal of Science Education*, 21(4), 373–388.

CHAUVET, F. (1994) Construction d'une compréhension de la couleur intégrant sciences, technique et perception: principes d'élaboration et évaluation d'une séquence d'enseignement. Unpublished Thesis, Université de Paris 7.

Chauvet, F. (1996) Teaching colour: design and evaluation of a sequence. *European Journal of Teacher Education*, 19(2), 119–134.

Chinn, C. and Brewer, W. (1993) The role of anomalous data in knowledge acquisition: a theoretical framework and implications for science instruction. *Review of Educational Research*, 63, 1–49.

Dewey, I. and Dykstra, D. I. (1992) Studying conceptual change: constructing new understandings. In R. Duit, F. Goldberg and H. Niedderer (eds.) *Research in Physics Learning: Theoretical Issues and Empirical Studies* (Kiel: IPN), 40–58.

Driver, R. and Bell, B. (1986) Students' thinking and the learning of science: a constructivist view. *The School Science Review*, 67, 443–456.

Driver, R. and Erickson, G. (1983) Theories in action: some theoretical and empirical issues in the study of students' conceptual frameworks in science. *Studies in Science Education*, 10, 37–60.

Driver, R. and Oldham, V. (1986) A constructivist approach to curriculum development in science. *Studies in Science Education*, 13, 5–12.

Duit, R. (1991) On the role of analogies and metaphors in learning science. *Science Education*, 75(6), 649–672.

Duit, R. (1999) Conceptual change approaches in science education. In W. Schnotz, S. Vosniadou and M. Carretero (eds.) *New Perspectives on Conceptual Change* (Amsterdam: Pergamon), 263–282.

Duit, R., Goldberg, F. and Niedderer, H. (1992) *Research in Physics Learning: Theoretical Issues and Empirical Studies* (Kiel: IPN).

Duit, R., Roth, W.-M., Komorek, M. and Wilbers, J. (1998) Conceptual change cum discourse analysis to understand cognition in a unit on chaotic systems: towards an integrative perspective on learning in science. *International Journal of Science Education*, 20, 1059–1073.

Dumas-Carre, A. and Weil-Barais, A. (1998) *Tutelle et médiation dans l'éducation scientifique* (Berne: Peter Lang).

Dupin, J.-J. and Johsua, S. (1994) Analogies et enseignement des sciences: une analogie thermique pour l'électricité. *Didaskalia*, 3, 9–26.

Evangelinos, D., Psillos, D. and Valassiades, O. (2002) An investigation of teaching and learning about measurement data and their treatment in the introductory physics laboratory. In D. Psillos and H. Niedderer (eds.) *Teaching and Learning in the Science Laboratory* (Dordrecht, Boston, MA and London: Kluwer Academic Publishers), 179–190.

Fensham, P. (2001) Science content as problematic – issues for research. In H. Behrendt, H. Dahncke, R. Duit, W. Gräber, M. Komorek, A. Kross and P. Reiska (eds.) *Research in Science Education – Past, Present, and Future* (Dordrecht: Kluwer Academic Publishers), 27–41.

Galili, I. (1996) Students' conceptual change in geometrical optics. *International Journal in Science Education*, 18, 847–868.

Gilbert, J. K. and Boulter, C. (1998) Learning science through models and modelling. In B.J. Fraser and K.G. Tobin (eds.) *International Handbook of Science Education* (Dordrecht, Kluwer Academic Press), 53–67.

Glynn, S. M. (1991) Explaining science concepts: a teaching with analogies model. In S. M. Glynn, R. H. Yeany and B. K. Britton (Eds.) *The Psychology of Learning Science* (Hillsdale, NJ, Lawrence Erlbaum), 219–240.

Guzetti, B. J., Snyder, T. E., Glass, G. V. and Gamas, W. S. (1993) Promoting conceptual change in science: A comparative meta-analysis of instructional interventions from reading education and science education. *Reading Research Quarterly*, 28, 116–159.

Hewson, P.-W. and Thorley, N.-R. (1989) The conditions of conceptual change in the classroom. *International Journal of Science Education*, 11, 541–553.

Johsua, S. and Dupin, J.-J. (1989) *Représentations et modélisations: le 'débat scientifique' dans la classe et l'apprentissage de la physique* (Berne: Peter Lang).

Kaminski, W. (1991) Optique élémentaire en classe de quatrième: raisons et impact sur les maîtres d'une maquette d'enseignement. Unpublished Thesis, Université de Paris 7.

Kariotoglou, P. and Tselfes, V. (2000) Science curricula: epistemological, didactical and institutional approach. *Physics Review*, 31, 19–28 (in Greek).

Kariotoglou, P., Koumaras, P. and Psillos, D. (1995) Différenciation conceptuelle: un enseignement d'hydrostatique fondé sur le développement et la contradiction des conceptions des élèves. *Didaskalia*, 7, 63–90.

KARIOTOGLOU, P., PSILLOS, D. and TSELFES, V. (2003) Modelling the evolution of a teaching–learning sequence: from discovery to constructivist approaches. In D. Psillos, P. Kariotoglou, V. Tselfes, G. Fassoulopoulos, E. Hatzikraniotis and M. Kallery (eds.) *Science Education in the Knowledge Based Society* (Dordrecht: Kluwer Academic Publishers), forthcoming.

KATTMANN, U., DUIT, R., GROPENGIEBER, H. and KOMOREK, M. (1995) A model of Educational Reconstruction. Paper presented at The NARST annual meeting, San Francisco, CA.

KOMOREK, M., STAVROU, D. and DUIT, R. (2001) Nonlinear physics in upper physics classes: educational reconstruction as a frame for development and research in a study of teaching and learning basic ideas of nonlinearity. In D. Psillos et al. (eds.) *Proceeedings of the Third International Conference on Science Education Research in a Knowledge Based Society* (Thessaloniki: Art of Text Publications), 483–485.

KORTLAND, J. (2001) *A Problem Posing Approach to Teaching Decision Making about the Waste Issue* (Utrecht: CDiβ Press).

KOUMARAS, P., PSILLOS, D. and KARIOTOGLOU, P. (1997) Causal structures and counter-intuitive experiments in electricity. *International Journal of Science Education*, 19, 617–630.

LEACH, J. and SCOTT, P. (2002) Designing and evaluating science teaching sequences: an approach drawing upon the concept of learning demand and a social constructivist perspective on learning. *Studies in Science Education*, 38, 115–142.

LEMEIGNAN, G. and WEIL-BARAIS, A. (1994) Developmental approach to cognitive change in mechanics. *International Journal of Science Education*, 16(1), 99–120.

LIJNSE, P.-L. (1994) La recherche-développement: une voie vers une 'structure didactique' de la physique empiriquement fondée. *Didaskalia*, 3, 93–108.

LINJSE, P.-L. (1995) 'Developmental Research' as a way to an empirically based 'Didactical Structure' of science, *Science Education*, 79(2), 189–199.

MÉHEUT, M. (1982) Combustions et réaction chimique dans un enseignement destiné à des élèves de sixième. Thèse de troisième cycle. Université de Paris 7.

MÉHEUT, M. (1997) Designing a learning sequence about a pre-quantitative model of gases: the parts played by questions and by a computer-simulation. *International Journal of Science Education*, 19(6), 647–660.

MÉHEUT, M. (2001) Two aspects of the relations between research and development. In D. Psillos, P. Kariotoglou, V. Tselfes, G. Bisdikian, G. Fassoulopoulos, E. Hatzikraniotis and M. Kallery (eds.) *Proceedings of the Third International Conference on Science Education Research in the Knowledge Based Society* (Thessaloniki: Art of Text Publications), 239–241.

MÉHEUT, M. and CHOMAT, A. (1990) The bounds of children atomism; an attempt to make children build up a particulate model of matter. In P.L. Lijnse et al. (eds.) *Relating Macroscopic Phenomena to Microscopic Particles* (Utrecht: CDβ Press), 266–282.

MÉHEUT, M. and PSILLOS, D. (orgs.) (2000) Designing and validating teaching–learning sequences in a research perspective. An international symposium, Paris.

MINSTRELL, J. (1992) Facets of students' knowledge and relevant instruction. In R. Duit, F. Goldberg and H. Niedderer (eds.) *Research in Physics Learning: Theoretical Issues and Empirical Studies* (Kiel: IPN), 110–128.

MORTIMER, E. F. (1993) The evolution of students' explanations for the physical state of matter as a change in their conceptual profile. In P.-L. Lijnse (ed.) *European Research in Science Education: Proceedings of the First PhD Summerschool* (Utrecht: CDβ Press), 281–287.

NIEDDERER, H. (1997) Learning process studies in physics: a review of concepts and results. Paper presented at 1997 AERA Annual Meeting, Chicago, IL.

NIKOLOPOULOU, K. (1993) An investigation into the effect of IT on pupils' understanding of some science concepts and processes. In P.-L. Lijnse (ed.) *European Research in Science Education: Proceedings of the First PhD Summerschool* (Utrecht: CDβ Press), 206–214.

NUSSBAUM, J. (1989) Classroom conceptual change: philosophical perspectives. *International Journal of Science Education*, 11, 530–540.

NUSSBAUM, J. and NOVICK, S. (1982) Alternative frameworks, conceptual conflict and accomodation: toward a principled teaching strategy. *Instructional Science*, 11, 183–200.

PETRI, J. and NIEDDERER, H. (1998) A learning pathway in high-school level quantum atomic physics. *International Journal of Science Education*, 20(9), 1075–1088.

Psillos, D. (1998) Teaching introductory electricity. In A. Tiberghien, E.-L. Jossem and J. Barojas (eds.) *Connecting Research in Physics Education with Teacher Education* (http://www.physics.ohio-state.edu/~jossem/ICPE/BOOKS.html).

Psillos, D. and Kariotoglou, P. (1999) Teaching fluids: intended knowledge and students' actual conceptual evolution. *International Journal of Science* Education, 21, 17–38.

Psillos, D. and Méheut, M. (co-ords.) (2001) Teaching–learning sequences as a means for linking research to development. In D. Psillos, P. Kariotoglou, V. Tselfes, G. Bisdikian, G. Fassoulopoulos, E. Hatzikraniotis and M. Kallery (eds.) *Proceedings of the Third International Conference on Science Education Research in the Knowledge Based Society* (Thessaloniki: Art of Text Publications), 226–241.

Psillos, D., Koumaras, P. and Valassiades, O. (1987) Students' representations of electric current before, during and after instruction on DC circuits. *Journal of Research in Science and Technological Education*, 5, 185–189.

Psillos, D., Koumaras, P. and Tiberghien, A. (1988) Voltage presented as a primary concept in an introductory teaching on DC circuits. *International Journal of Science Education*, 10, 29–43.

Rainson, S. (1995) Superposition des champs électriques et causalité. Unpublished Thesis, Université D. Diderot, Paris.

Ravanis, K. and Papamichael, Y. (1995) Procédures didactiques de déstabilisation du système de représentations spontanées des élèves pour la propagation de la lumière. *Didaskalia*, 7, 43–61.

Rebmann, G. and Bugeat, V. (1994) Tentative d'utilisation remédiative de l'opposition des cadres qualitatif et quantitatif de raisonnement en électrocinétique. In M. Caillot (co-ord.) *Actes du quatrième séminaire national de la recherche en didactique des sciences physiques* (Amiens: Université de Picardie et IUFM), 23–36.

Robardet, G. (1995) Situations problèmes et modélisation; enseignement en lycée d'un modèle newtonien de mécanique. *Didaskalia*, 7, 131–143.

Schwedes, H. and Dudeck, W.-G. (1996) Teaching electricity by help of a water analogy. In G. Welford, J. Osborne and P. Scott (eds.) *Research in Science Education in Europe: Current Issues and Themes* (London: The Falmer Press), 50–63.

Schwedes, H. and Schmidt, D. (1992) Conceptual change and theoretical comments. In R. Duit, F. Goldberg and H. Niedderer (eds.) *Research in Physics Learning: Theoretical Issues and Empirical Studies* (Kiel: IPN), 188–202.

Scott, P. H. (1992) Pathways in learning science: a case study of the development of one student's ideas relating to the structure of matter. In R. Duit, F. Goldberg and H. Niedderer (eds.) *Research in Physics Learning: Theoretical Issues and Empirical Studies* (Kiel: IPN), 203–224.

Scott, P. H., Asoko, H. M. and Driver, R. H. (1992) Teaching for conceptual change: a review of strategies. In R. Duit, F. Goldberg and H. Niedderer (eds.) *Research in Physics Learning: Theoretical Issues and Empirical Studies* (Kiel: IPN), 310–329.

Sere, M.-G. (1985) Analyse des conceptions de l'état gazeux qu'ont les enfants de 11 à 13 ans, en liaison avec la notion de pression, et propositions de stratégies pédagogiques pour en faciliter l'évolution. Unpublished Thesis, Université de Paris 6.

Sere, M.-G. and Chomat, A. (1983) Les représentations des élèves de sixième et leur évolution. Etat gazeux. *Rapport de l'équipe parisienne de la recherche: étude des représentations préalables de quelques notions de physique et leur évolution* (Paris: INRP et LIRESPT), 19–32.

Stavy, R. and Berkovitz, B. (1980) Cognitive conflict as a basis for teaching quantitative aspects of the concept of temperature. *Science Education*, 64, 679–692.

Tiberghien, A. (1996) Construction of prototypical situations in teaching the concept of energy. In G. Welford, J. Osborne and P. Scott (eds.) *Research in Science Education in Europe. Current Issues and Themes* (London: Falmer Press), 100–114.

Tiberghien, A. and Barboux, M. (1983) Les représentations des élèves de sixième et leur évolution. Température-chaleur. *Rapport de l'équipe parisienne de la recherche: étude des représentations préalables de quelques notions de physique et leur évolution* (Paris: INRP et LIRESPT), 6–18.

Tiberghien, A., Psillos, D. and Koumaras, P. (1995) Physics instruction from epistemological and didactical basis. *Instructional Science*, 22, 423–444.

Thiis, G. D. (1992) Evaluation of an introductory course on 'force' considering students' preconceptions. *Science Education*, 76(2), 155–174.

TRUMPER, R. (1990) Being constructive: an alternative approach to the teaching of the energy concept – part one. *International Journal of Science Education*, 12(4), 343–354.

TSOUMPELIS, L. (1993) Explications et modèles dans des situations a-didactiques en sciences physiques: le cas de la concentration molaire. Thèse de doctorat, Université de Lyon 1.

VIENNOT, L. and RAISON, S. (1999) Design and evaluation of a research-based teaching sequence: the superposition of electric field. *International Journal of Science Education*, 21, 1–16.

VIIRI, J. and SAARI, H. (2004) Research based teaching unit on the tides. *International Journal of Science Education*, 26, 463–482.

VOLLEBREGHT, M. J. (1998) *A Problem Posing Approach to Teaching an Initial Particle Model* (Utrecht: CDβ Press).

VON GLASERSFELD, E. (1992) A constructivist view of learning and teaching. In R. Duit, F. Goldberg and H. Niedderer (eds.) *Research in Physics Learning: Theoretical Issues and Empirical Studies* (Kiel: IPN), 29–39.

WEIL-BARAIS, A. and LEMEIGNAN, G. (1990) Apprentissage de concepts et modélisation. *European Journal of Psychology of Education*, 5, 391–415.

WELZEL, M. (1998) Emergence of complex cognition during a unit on static electricity. *International Journal of Science Education*, 20, 1107–1118.