International Journal of Science Education

ISSN: 0950-0693 (Print) 1464-5289 (Online) Journal homepage: http://www.tandfonline.com/loi/tsed20

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INT. J. SCI. EDUC., 16 APRIL 2004, VOL. 26, NO. 5, 555–578

Special Issue

An epistemological analysis of the evolution of didactical activities in teaching–learning sequences: the case of fluids

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In the present paper we propose a theoretical framework for an epistemological modelling of teaching–learning (didactical) activities, which draws on recent studies of scientific practice. We present and analyse the framework, which includes three categories: namely, Cosmos– Evidence–Ideas (CEI). We also apply this framework in order to model *a posteriori* the didactical activities included in three successive teaching–learning sequences in the field of fluids, developed gradually by the same researchers over several years under evolving dominant approaches to science teaching and learning (transmission, discovery, constructivist). For each sequence we analyse the planned activities included in student and teacher documents in terms of the CEI model. We deduce the suggested links (or lack of them) between the three categories and discuss the opportunities that students would have during science teaching to link in each sequence the world of theories with real things.

Background

Following research into students' conceptions (Driver et al. 1998) and theoretical positions on constructivism as a referent for science teaching and learning (Tobin and Tippins 1993), several science education researchers started making use of these significant empirical and theoretical developments in order to improve science teaching. Researchers were interested in designing, trying out and evaluating specific activities such as experiments enhancing cognitive conflict (Nussbaum and Novick 1982), teaching approaches such as those aiming at conceptual change (Hewson et al. 1998), units or topic-oriented teaching sequences, in specific phenomenological fields but rarely, if at all, whole scale curricula (Driver and Oldham 1986), in a variety of educational contexts. An assumption shared by several science educators was that scientific understanding involves several aspects of scientific inquiry: understanding representations of the material world in terms of concepts and models, but also ways of linking representations with material phenomena and intervention procedures onto the material world. Enhancement of student interactions with the material world in laboratory settings remained, at least for several researchers, an important focus of constructivist teaching approaches, although researchers' interests and practices in student laboratory activities seemed to shift away from the discovery approaches that long dominated pedagogical innovations in science education.

International Journal of Science Education ISSN 0950–0963 print/ISSN 1464–5289 online
http://www.tandf.co.uk/journals
DOI: 10.1080/0950069031000161474

We may distinguish two particular recent research directions (there are others) bearing primarily on the development of more effective constructivist approaches to teaching science: one focusing on students' learning, and the other on representations of scientific knowledge (conceptual and/or procedural). In the first, following the modelling of student's conceptions, the research focus lies in the monitoring and micro-analysis of student conceptual evolution, as well as learning outcomes, in the context of a scientific topic (Niedderer 1997). In the second direction, the research focus lies in the transformation of scientific knowledge according to instructional aims into knowledge adapted to students' conceptions and the evolution of these conceptions during teaching. Here, work on innovative content representations and their links with the material world, although arguably not widely disseminated (Fensham 2001), moved away from reflections on, say, the difficult aspects of scientific content and the design of new experiments towards developing knowledge to be taught that is learnable by the students.

One developing practice aimed at combining the aforementioned directions involves the development and publication of topic-oriented sequences in various areas, such as optics, structure of matter, heat, electricity and fluids, by researchers who consider that the learning of science is a constructive activity and treat the usual science content as problematic (Galili 1996, Méheut 1997, Millar and Osborne 1998, Psillos 1998). Recently, in international meetings, Méheut and Psillos (2000) and Psillos and Méheut (2001) introduced the term teaching–learning sequence (TLS) to identify the potential construction of fruitful links between the designed teaching and expected student learning as a distinguishing feature of a research-based medium-scale curriculum development aiming at bringing research and teaching closer, in several contexts, than is the normal practice. A TLS is often both a research process and a product like a traditional curriculum unit package, which includes well-researched teaching/learning activities (Méheut and Psillos, this volume). Often a TLS develops gradually out of several applications according to a cycling evolutionary process enlightened by research data, which results in the enrichment of this TLS with empirically validated expected student outcomes from the planned activities (Linjse 1995).

The development of a TLS has become the focus of several theoretical and empirical studies, which are extensively reviewed elsewhere (see Méheut and Psillos, this volume). A review of published papers shows that these are frequently presentations of student learning outcomes resulting from various TLS, which are extensively discussed by the researchers. However, the explicit and implicit assumptions and decisions that affect, to a considerable degree, the design and development of the corresponding teaching approaches are less widely treated and may not even be clearly presented. The construction of a teaching content adapted to students' minds seems to involve implicit expertise and special practices on the part of the researchers. For example, the developers' underlying epistemological assumptions, which inevitably bear upon the design of the sequences, are hardly ever made explicit (with some notable exceptions; for example, Tiberghien 2000). This makes the communication and replication of teaching approaches, beyond broad assumptions, problematic even in widely discussed areas like the structure of matter or simple electrical circuits, and raises concerns about the validity of these approaches in different contexts.

Since the construction of a TLS often involves subsequent versions developed over a long period by a researcher or a research team, we suggest that the analysis and comparison of such various versions may become a fruitful research approach, aimed at revealing possible patterns in the practices and hidden assumptions held by the specific researcher. As explained in the following, our proposal is based on recent studies of scientific practice. To a certain extent, the retrospective analysis of assumptions and practices put into effect in a series of TLSs has drawn the attention of science education researchers from various perspectives. Teaching proposals and related student learning results were discussed by Brown (1992), who provided a remarkable account of the evolution of teaching–learning activities linking content representations with relevant experiments included in successively developed TLSs in mechanics. The researcher called this method of development trying out and gradually adapting scientific content to students' minds in the form of teaching experiments, in line with suggestions from mathematics education (Steffe and D' Ambrosio 1996). Méheut (1997) developed different versions of TLSs aiming at a gradual enrichment of links between the material world and scientific models on the structure of matter by employing certain innovative experiments in combination with simulations of microscopic particles. Later, Méheut (1998, this volume) traced the developmental history of several sequences in an attempt to illuminate assumptions and factors implicitly or explicitly affecting researchers' work. Duit et al. (1997) have investigated successive variations of a TLS on chaos theory, emphasizing either the conceptual evolution of the students or the structure and effectiveness of the teaching. Among other issues, the proposed teaching–learning activities include innovative links between experiments and reconstructed scientific theories according to the perceived aims of instruction.

As already mentioned, we recently suggested an approach for revealing the features involved in the development of a series of TLSs that is based on the socio-constructivist epistemology of science (Kariotoglou et al. 2003). We followed Pickering (1992, 1995), who attempts to analyse the practice of scientists by modelling the relations between the scientist's knowledge, handling beliefs and experiences as well as his social/institutional relationships. We consider that, in science education, the science education scientist (or didactician) through his practices connects (a) the educational and institutional, (b) the material and physical, and (c) the scientific factor (i.e. science education) with his/her product, which in our case is a TLS. We refer to scientific factor as the constraints in the science educator's work from the dynamics and traditions of his/her scientific community similar to those that contribute to the development of a scientific 'paradigm'. The science educator's scientific practice on the one hand exposes the features of a series of TLSs, which either change or remain stable as time passes, and on the other reveals the relations between the stability or variability of the features and the factors that influence the science educators' scientific work running over the evolution of particular TLSs. We argued that features of the science educator's practice may, at several levels, derive from the analysis of the corresponding teaching materials included in the various TLSs he/she has developed. As a case study, we attempted a retrospective critical review of three successive TLSs in the field of fluids that we developed over a period of several years, in order to demonstrate factors that affected their design and revisions. We found that, on any given occasion, variations in the practice of the scientists (didacticians) involved in the making of these TLSs were related to the prevailing approaches to science teaching and learning – namely transmission, discovery and constructivist – which constitute the scientific factor influencing their practice. Yet this relation took place in a context determined by educational and material factors, which are often not taken into account in researchers' accounts of published TLSs. We also found that, despite variations, the laboratory character of these TLS remained constant all along the sequences.

The afore-mentioned laboratory-based TLSs on fluids were broadly shaped by scientific (in the science education context), institutional/educational and material factors, but the specific teaching–learning activities were also affected by the designer's view of scientific inquiry. We consider that these TLSs, like several others, have embedded characteristics of scientific inquiry worthy of serious examination. Prominent among them are the suggested practices for students to link theoretical entities and the material world, which lie at the heart of scientific inquiry. We argue that such characteristics, often being implicit, are embedded in the proposed teaching–learning activities included in each TLS. In this context, our aims in the present paper are twofold. On the one hand we propose a general framework for modelling didactical activities, which draws on recent studies of scientific practice (Hacking 1992). In effect we introduce an explicit epistemological framework for modelling activities in TLSs that considers scientific practices as a pre-eminently stabilizing factor in scientific activity. On the other, we apply this framework in order to model – *a posteriori* – the didactical activities included in the afore-mentioned TLS in fluids, and thus describe in a unifying language the changes that took place over a lengthy period in the designer's planning for engaging students in scientific inquiry. We argue that this framework, starting with epistemic dimensions of didactical activities, proceeds to a categorization of them that facilitates their didactical manipulation.

Mode of inquiry

The choice of theoretical framework

Currently, several researchers and projects (American Association for the Advancement of Science 2003, Bybee and Champagne 2000, Millar and Osborne 1998, Programme for the International Student Assessment 2003, UNESCO), in discussing the aims of science education, more or less suggest that science education should aim at delivering to students scientific knowledge that is useful in everyday life by developing their understanding of representations of the material world. Students should understand how scientists represent the world in terms of concepts and models, as well as the choice and use of these models in coping with their everyday needs and in communicating with their social milieu. Yet science involves not only representations of the world, but ways of intervening in things by putting them to work in the laboratory according to theories and models. This sort of laboratory-centred interventionist practice has a powerful and prevailing tradition in science, interacts and supports theoretical productions and distinguishes scientific literacy from other types of literacy (e.g. philosophical or literary). Science education has in one way or another always respected this fundamental aspect of scientific knowledge, as evidenced from the long history and current trends in laboratory work across educational systems (Psillos and Niedderer 2002). We consider that if laboratory practices are ignored or minimized then science education should be radically restructured, emphasizing only the representational aspect of scientific knowledge, turning the field into something like natural philosophy.

We consider that understanding science implies some understanding of the practices involved in scientific inquiry, aspects of which are and should be included in the teaching of scientific subjects to students. Yet we feel that a rationally constructed modelling of links between the representational (theories and models) and the practical interventionist practice of science is to a considerable extent missing in science education, despite thorough discussions in every part of the world.

In choosing our theoretical framework we were influenced by the work of Hacking (1992, 1995), who starts by considering the actual laboratory science activities practised by scientists and then, by working upwards, attempts to generalize and produce patterns of scientific practice. To the best of our knowledge this is the only approach that does not draw on the social and cognitive characteristics of communities of scientists, which are certainly different from communities of students. We consider that this feature of Hacking's approach is a considerable advantage, providing the theory with versatility and potential for didactical recontextualization. We choose to study activities involved in scientific inquiry within educational settings, which in the present case concern the previously mentioned TLSs on fluids. The detection and analysis draw on a model attempting to describe, as adequately as possible, all the possible activities characterizing laboratory sciences in accordance with Hacking (1992).

Modelling scientific practice

In line with Hacking, who studied the practices of scientists engaged in laboratory sciences, we claim that there are three major categories of entities internal to scientific inquiry. These are: material entities ('things' and 'raw data'; Hacking 1992: 44) realizing the phenomenon in the real world, which we call Cosmos; Evidence (assessed, analysed, reduced, etc., quantitative or qualitative data) as considered appropriate by the experimenter; and Ideas (concepts, theories, models, beliefs, etc.) about the natural phenomenon under consideration. In the category of Cosmos, for instance, we include all materials and artefacts used in one way or another, such as devices, measurement instruments and samples, as well as the instrument readings that constitute the raw data. These last are considered as constructions/material products of experimentation and not as entities provided by nature. In Evidence, we tend to include the representing entities derived either from the senses (what we see, hear and feel) or from a more or less systematic processing of raw data; that is, by selecting some of them, representing them in specific ways, classifying them according to chosen criteria, comparing them with other data, etc. In the category of Ideas, we include very specific theoretical entities, such as a systematic theory, a model or a concept and the methodological entities that gain a certain meaning in a theoretical framework, which can be a question or a hypothesis. We also include implicit views (i.e. views of reality, causality, relation between the subject of the knowledge and the external world) that, although not straightforwardly stated, influence the construction of scientific knowledge.

Our model involves three categories in play in scientific inquiry, whereas other theorists and researchers employ only two; namely, the world of ideas and the material world. Certain remarks ensue. We consider that one problem in the often-employed two-level approach of scientific inquiry involving the material world and the world of ideas (theories, models) is that, frequently, the entities involved in

Cosmos are mixed with entities involved in the category of Evidence or with Ideas, in accordance with the Cosmos–Evidence–Ideas (CEI) categorization. In the first case, Cosmos is reduced, in accordance with empirical tradition, to 'what we see'; in the second case, Cosmos is identified with its representation according to a specific scientifically valid theory in line with a positivistic perspective. We believe that in this way the possibility of a critical approach to either Evidence or Theories is reduced. What is reduced, in other words, is the potential of experimentally intervening in a unique Cosmos, independent of Evidence and Ideas, in order to validate either Ideas or Evidence.

At this point we should note that the separation of the entities represented by Ideas and Evidence could be compared with the philosopher's distinction of the terms of scientific discourse as theoretical and observational (Boyd 1991: 7–10). We consider that this analogy does not apply in our approach, which attempts to classify functional entities of activities of scientific inquiry and not the terms of the discourses philosophers use or produce.

Scientific ideas and evidence are entities that represent real phenomena and explain or justify one another. They are entities of the 'world in mind' through which one may represent a phenomenon of the 'real world'. On the other hand, the specific phenomenon as a part of the 'real world' is out there, in for example a laboratory, but it is not communicable. One may intervene in the material world, for example in the laboratory, making things work one way or another using his/her ideas or aiming at some expected evidence, but the real part of the phenomenon (which exists or is constructed) does not speak for itself. This hypothesis makes it difficult to talk of the entities of the 'real world' without making use of any evidence or ideas that link to these entities. That happens because representations are prerequisites of discourse. We consider that the 'real world' cannot be ignored, because on the one hand its existence limits the variety of evidence and ideas that can be used for its representation. That means we do not consider that the construction of representations is only a social procedure, quite independent of the part of the 'real world' to which it belongs. On the other hand, the relation Cosmos–Evidence or Cosmos–Ideas is a multi-faceted one, with several meanings. In other words, a piece of the real world may be represented by several kinds of evidence or ideas. For example, a glass may be a glass of water, a transparent cylindrical container containing an assortment of molecules, as half filled with water or half empty: all these statements are descriptions of the same pieces of the material world, bearing on similar evidence or ideas

In scientific inquiry, scientists carry out activities as connections among these three different categories of entities – Cosmos, Evidence, Ideas – aiming at the self-vindication of their scientific activity. We consider that the practices of scientists engaged in scientific inquiry are characterized by the kinds of connections among these entities, perceived within the adopted framework, which in our case involves the afore-mentioned categories as well as the ways of linking them. In a schematic approach this three-level model of scientific inquiry, called the CEI model, is depicted in figure 1. This model depicts the distinction between the world of phenomena and the world of representation, which is differentiated into two categories, Ideas and Evidence. The model shows not only the entities, but also the fact that during the course of inquiry scientific activities involve two-way interactions between entities, which are potentially modified by one another. We may note that the model is at once general and generic. In other words, the model

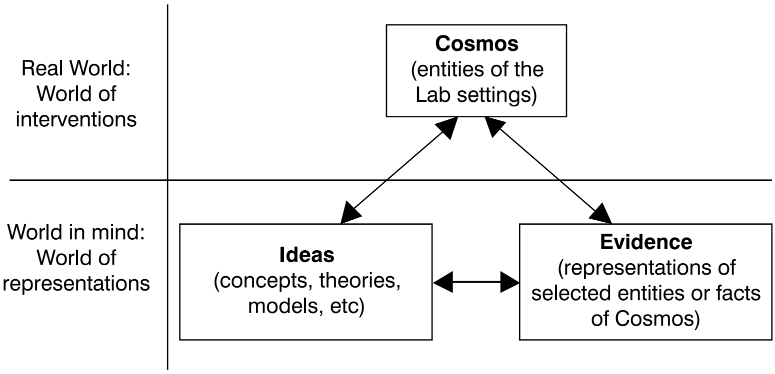

Figure 1. The Cosmos–evidence–Ideas (CEI) model of scientific inquiry.

refers to all the entities involved in each category without specifying particular interactions between specific entities. These may come out at a more concrete level, which is beyond the scope of the present paper.

Modelling didactical activities

We consider that approaching practices of scientific inquiry in terms of patterns of connections between the entities of Cosmos, Evidence and Ideas does not apply only to professional settings, but to educational ones as well. This assumption does not imply that the variety of possible patterns is similar for students and scientists, which could be considered the basis of the metaphor of the student as scientist. We agree with other researchers that scientific understanding requires learners to construct links between the representations of phenomena and the material world (Tiberghien 1994). Recent findings point out that, particularly when students are engaged in interventions onto the material world in the laboratory, the linking of scientific theories with practical activities is not easily achieved, even by mature students (Bécu-Robinault 2002, Niedderer et al. 2002, Sander et al. 2002).

In the following paragraphs we present some examples of how the CEI may be applied in educational settings in order to illustrate possible connections between Cosmos, Evidence and Ideas embedded in possible teaching–learning activities. In order to save space, the various links between the CEI categories are hereafter codified in brackets. For example, the proposed linking of empirical evidence with the material world is codified as Evidence → Cosmos. The arrows indicate the direction of the linkage: for example, the Evidence → Cosmos linking implies intervention onto the material world in terms of specific Evidence, whereas the extraction of evidence from raw data is denoted by the link Cosmos → Evidence

Let us consider the case of a guided experiment. A teacher asks a student to fill a syringe with water. We consider that what the student is actually being asked to do is to construct (i.e. to intervene in) a segment of the real world, which cannot be described in its actual variety and complexity, on the basis of some specific evidence: that is, a syringe full of water. The teacher could ask his/her students to intervene in this segment of the world on the basis of a specific piece of evidence. The student is asked, in other words, to realize a linking Evidence → Cosmos. In the same way, if another teacher specifically asks a student to push the piston while holding a finger over the opening of the water-filled syringe, then in effect this student is being asked to modify that segment of the real world according to some specific evidence (Evidence → Cosmos). Later on, when the teacher asks the student to describe what is happening, he/she is asking him to extract a new piece of evidence; that is, to realize a linking between Cosmos → Evidence, and to answer that the piston in the syringe is not moving. In the same experimental setting the teacher could ask a student to predict the evidence before performing the experiment. In this case we consider that the student is asked to predict the evidence by using his own ideas: that is, to realize a linking between Ideas → Evidence. When, finally, the teacher asks for an interpretation, he/she is actually asking the student to explain the specific evidence in terms of some specific (scientific or common) ideas; that is, to realize a linking between Evidence → Ideas.

Understanding a theory demands a direct linking of Cosmos → Ideas, which implies the recall and use of the proper theory, model or concepts for the description of the function of a physical phenomenon. This is easy when students use their own ideas, drawn from their everyday life experiences. For example, it is very easy for them to imagine that an 'internal force' pushes a free-moving body without having or looking for any evidence that such a force exists (e.g. observing an internal force on the moving body). Yet the same linking is extremely difficult when the scientific (Newtonian) concept of force is employed. Besides, we consider that one understands scientific ideas (concepts /theories) when they are included in one's approach to the material world. For example, one may understand Newton's conceptualization of movement if one considers space as isotropous, homogeneous and unlimited, without having any specific evidence for these views about space. If one wants to understand the special theory of relativity, one should revise such views on space for exactly the same phenomena and evidence. In another case, one may understand the Pascal principle if one 'sees' pressure variation all through a volume of liquid without having any evidence for variation. Then one may advance one's thinking and wonder whether variations in pressure are transmitted in terms of limited or unlimited speed.

The interventionist use of an Idea may, for example, be embedded in an open investigation, in which, for instance, a student is required to construct an experimental set-up, functioning in terms of a scientific model. In this case a direct Ideas → Cosmos linking is required of the student.

It is important to note that, in science education research, types of links between the entities of scientific experimentation have been analysed and researched in proposed teaching–learning activities as well as during actual student interactions in the classroom and the lab (Buty 2002, LeMaréchal et al. 2001, Millar et al. 2002, Niedderer et al. 2002). These studies contribute important insights and rich findings on either the proposed types of links in teaching–learning activities or the ones actually achieved by students. Yet up to now it seems that, in one way or another, these researchers have been utilizing a two-level categorization involving the Material world and Theories/Models. Accordingly, they study either the proposed links in teaching–learning activities or the links achieved during classroom interactions between the material world and the world of Theories/ Models. Broadly speaking, in terms of the CEI categories, Ideas and Cosmos are employed, but not Evidence as a distinct category. Our concerns about such an approach were raised in the previous section.

Finally, we consider that the employment of the CEI model has the advantage of allowing a – fruitful for science teaching – distinction to be drawn between interventions onto the material world on the basis of an idea or specific evidence (i.e. connecting I → C or E → C) and representations of the material world (i.e. connections like I → E, E → I, C → I or C → E). CEI discerns between the connections in which, potentially, the linguistic factor holds the most important role (connections that are constructed by using the representational capacity of language; i.e. inductive or deductive reasoning), like I → E or E → I, and the ones where the material factor should be expected to be more important (connections that are constructed using the interventional capabilities of the experimenters; i.e. skills), like E → C or I → C.

Construction and analysis of the data

As discussed elsewhere, three teaching sequences were developed by the same group in the area of fluids in a changing educational and scientific landscape over the past 20 years (Kariotoglou 2002, Psillos and Kariotoglou, 1999). We consider these three sequences as three successive TLSs, namely TLS1, TLS2, TLS3.

Methodologically, one may detect practices at either the pro-active or the interactive phase of teaching, but the data are of a different nature in each case. Plans, student worksheets, teaching guidelines suggesting activities, the objectives of the activities and the underlying theoretical foundations are documents that may constitute data for the pro-active phase; classroom verbal interactions or student and teacher actions are examples of potential data for the interactive phase. In the present paper, which involves an *a posteriori* review of already developed TLSs, we focus on the proactive phase of each TLS, looking for proposed important links between the material world and theoretical entities in suggested teaching–learning activities. Elsewhere, we have focused on aspects of the interactive phase in the context of TLS3 (Kariotoglou et al. 1999). Our data also include activities in the context of the official curriculum/textbook in use when each TLS was begun, in order to have a reference point.

The data were constructed as follows. Each TLS was documented in terms of the relevant teacher guidelines, plans and sheets and student worksheets. Both types of material contain descriptions of the activities suggested for the teachers and the students. As mentioned in the first section of this paper, we consider that the content and the structure of these materials reflect, implicitly or explicitly, the assumptions about scientific inquiry held by the developers.

The activities in the teaching materials were analysed in terms of the CEI model. Our assumptions about the practices of scientific inquiry in diverse settings allows us to attempt to model the proposed teaching–learning activities in order to reveal possible practices for linking Cosmos, Evidence and Ideas. An analysis of TLS materials may take place at different levels. For example, researchers may focus on the micro-level of separate activities included in one worksheet, looking for patterns and/or their frequencies. In our previous work (Kariotoglou et al. 2003) we provided a global analysis of the evolution of the TLSs on fluids in order to demonstrate the factors that affected their design and revisions over several years. In the present work we opted for an intermediate level. More specifically, we chose as a unit of analysis any specific part of the text (either for the teacher or the students) describing a teaching–learning activity with a specific set of objectives and proposed actions for achieving them. These descriptions may refer to types of teaching–learning activities, irrespective of the specific topics, such as lectures, demonstration experiments by the teacher or guided experiments for the students. Then we located the different types of such teaching–learning activities in each TLS and correlated them with connections between Cosmos, Evidence and Ideas. In this way we were able to identify what kinds of practices are suggested in each TLS and what are not. Focusing on the pro-active phase, we were interested in the variety and features of the proposed feasible practices on different didactical occasions rather than on their actual classroom application or local effectiveness, which in any case was not feasible in this type of *a posteriori* analysis.

The analyses were carried out, in an initial stage, by two of the authors, independently, and their results were validated afterwards during the three researchers' discussions, until agreement was reached. It may be noted that two of the researchers were involved in the development of the TLSs, while the third, who was involved only in the validating discussion, joined later.

Results

Detailed accounts of the TLSs in the area of fluids have been published elsewhere (Kariotoglou 2002, Kariotoglou et al. 1995, Psillos and Kariotoglou 1999). In the present section we present and describe briefly the three TLSs and the official curriculum in terms of their content, main learning objectives, main teaching–learning activities and major learning outcomes. As previously stated, the main aim is to present a retrospective analysis of teaching–learning activities in terms of the CEI model for each TLS separately in order to detect the links between Cosmos, Evidence, Ideas that are proposed to be realized in the context of each TLS. We deliberately opted not to include extensive learning results, for several reasons: first, these have been published in detail in the previously stated studies; second, space restrictions do not allow an extensive account, which would not do justice to the studies; third, not all TLSs were applied to the same population. For example, TLS3 addressed the procedural and conceptual knowledge of prospective teachers while TLS2 focused on the conceptual knowledge of pupils.

The practices included in the Official Curriculum

In the late 1970s and early 1980s in Greece, the official curriculum/textbook focused, in the section dealing with Fluid Mechanics, on concepts and laws: namely, the relation of force to pressure, the fundamental law of hydrostatics, atmospheric pressure, the factors affecting buoyancy, and the Pascal principle. In the relevant materials and the embedded didactical tradition, the proposed teaching–learning activities are dominated by lectures and a few demonstration experiments in the context of the prevailing transfer-of-knowledge approach to science teaching and learning. The stated learning objectives focus on the students' conceptual understanding of the topic.

Such teaching–learning activities promote only certain of the six possible connections among the C, I and E categories (see figure 1). To be more specific, it is normally expected that, during lecturing, students will be directed towards connecting the world of phenomena to that of scientific ideas. In the materials examined, the lectures actually provide students with the opportunity to connect

Table 1. The practices included in the Greek Official Curriculum.

Official Curriculum: didactical proposal (in terms of activities)	*Cosmos → Ideas*	*Ideas → Cosmos*	*Cosmos → Evidence*	*Evidence → Cosmos*	*Ideas → Evidence*	*Evidence → Ideas*
A. Lecture					Prediction of expected evidence based on scientific ideas	Recalling evidence from experience relevant to scientific ideas Interpretation of relevant evidence
B. Rarely: demo experiments			Demonstration of evidence by the teacher from experimental set-ups			

empirical evidence from their own experiences to some scientific ideas (Evidence → Ideas). Students may also be asked to attempt an interpretation of some relevant evidence from everyday familiar phenomena (Evidence → Ideas). Besides, presentation of a scientific theory is often an attempt to establish or re-establish connections between scientific ideas. In some cases, the materials include demos aiming at the observation of some evidence out of pieces of the material world (Cosmos → Evidence). Of course, in this case students are guided to attempt predictions, and then are expected to make connections between scientific ideas and the anticipated evidence (Ideas → Evidence).

All the afore-mentioned links are presented in table 1, which is designed to illustrate the practices suggested by the official curriculum. The horizontal axis sets out all six possible connections among the three CEI entities (see also figure 1). The vertical axis lists the types of activities that were detected in the official documents. The cells indicate the proposed links revealed by our analysis of the materials. What is evident in table 1 is that the official curriculum promotes only some of the possible connections among the C, E and I categories. In particular, our analysis reveals a lack of proposed connections directly linking the material world and the world of ideas, the main weight falling on connections between Evidence and Ideas.

The practices included in TLS1

In the early 1980s the developers felt it necessary to introduce students to laboratory work. To that end a six-unit teaching sequence on Fluid Mechanics – the TLS1 – was developed, taking into account the basis of the official curriculum and the school textbook. TLS1 has been revised several times and applied to 13-year-old to 14-year-old compulsory education students (second form of Greek Gymnasium). The main objective of TLS1 is students' practice in experimental skills and some understanding of fluid concepts and laws in relation to everyday applications.

For reasons related to educational context, new TLS1 activities follow some lecturing on the basic concepts/principles of fluid phenomena in line with the official curriculum. The links attempted in such lecturing activities have already been described in the previous section.

Table 2. The practices included in TLS1.

Didactical proposal in terms of activities	*Cosmos → Ideas*	*Ideas → Cosmos*	*Cosmos → Evidence*	*Evidence → Cosmos*	*Ideas → Evidence*	*Evidence → Ideas*
A. Lecture					Prediction of expected evidence based on scientific ideas	Recalling evidence from experience relevant to scientific ideas Interpretation of relevant evidence
B. Students' guided discovery laboratory work with a rotating laboratory form			Extraction of Evidence by the students from raw data	Construction of experimental set-ups based on instructions by the students Production of raw data based on instructions		Interpretation of produced evidence

The main new (with regard to the official curriculum) teaching–learning activity suggested in the TLS1 materials is laboratory work carried out in small groups, using rotating laboratory exercises and structured worksheets. TLS1 was evolved and applied at a time when discovery approaches to teaching and learning science were dominant. For this reason, laboratory work was based on a guided discovery approach related to principles and laws such as the fundamental law of hydrostatics, atmospheric pressure, Pascal's principle, factors affecting buoyancy and their applications. For example, one experiment used is the compression/ extension of the piston of a syringe containing first water and then air, so that students, following instructions, can discover similarities and differences between liquids and gases.

This activity proposes the construction of pieces of the real world by the students themselves, on the basis of technical instructions. This actually implies that in the laboratory students are directed towards linking Evidence to Cosmos. In addition, students are asked to derive raw data following worksheet guidelines (Evidence → Cosmos). Further on, they are expected to extract evidence from raw data, which implies a link of Cosmos with Evidence. After this, they are guided towards the interpretation of this evidence in terms of scientific ideas (Evidence → Ideas). All these links are presented in table 2, which is designed to illustrate the suggested practices contained in TLS1. Table 2 shows that TLS1, which was the first TLS developed by the researchers, proposes a new link, that from Evidence to Cosmos, while the links between Ideas and Evidence are enriched. In effect, the students themselves are encouraged to intervene onto the material world, and not only to act at the representation level. The direct links between Cosmos and Ideas, however, remain inert.

Results have shown a remarkably positive pupil attitude towards laboratory work, as well as substantial familiarization with experimental skills on their part. This, however, was not the case at the conceptual level (Kariotoglou et al. 1988).

The practices included in TLS2

TLS2 was developed in the late 1980s, and is based on data regarding students' conceptions and on theoretical developments that suggest constructivism as a referent for science teaching and learning. TLS2 also involves concepts and models relating to fluids, and targets primarily conceptual learning, and particularly students' conceptual shifts from intuitive towards scientific knowledge. As far as students' conceptions about pressure are concerned, TLS2 utilizes a three-model classification – packed crowd, pressure–force, liquidness – in order to introduce and negotiate the pressure concept (Kariotoglou and Psillos 1993, Kariotoglou et al. 1995). To avoid reinforcing the pressure–force model (non-differentiation between pressure and force), pressure is introduced as a primary concept, qualitatively and experimentally, without connecting it with force. The necessity for such an approach arises from students' conceptions, which are reinforced by the introduction of the pressure concept in the traditional way ($P = F / s$). However, at the end of TLS2 the concepts of pressure and force are connected with each other, following activities on differentiating pressure from force, which are discussed later. In effect, it attempts an educational reconstruction of scientific content towards knowledge to be taught that is learnable by students. It may be noted that such a treatment of scientific knowledge was not widespread in science education at that time.

In comparison with TLS1, several new teaching–learning activities are implemented in TLS2, prompting a structured succession of connections between CEI entities.

More specifically, familiarization experiments are suggested in which the students are expected to predict what will happen to a planned set of phenomena in terms of their conceptions. In other words, what is different here from TLS1 in the handling of experiments is that the students are required to predict experimental evidence and attempt connections (Ideas → Evidence) according to what they themselves believe. After prediction, the students are required to construct pieces of the real world on the basis of available technical instructions. In effect the students are directed towards linking Evidence to Cosmos. Students are then guided to observe experimental outcomes, suggesting yet another connection (Cosmos → Evidence). In addition, raw data are derived according to worksheet guidelines (Evidence → Cosmos). Further on, extraction of evidence from raw data is attempted (Cosmos → Evidence), as well as interpretation of this evidence (Evidence → Ideas). The outcome is that students attain a large number of connections (Ideas → Evidence and Evidence → Ideas) through these introductory experimental activities and related discussion within their working groups.

Students are then guided through activities concerning the classification of materials into the three states of matter, using special worksheets, in whole classroom discussions. Such classification is planned to follow familiarization experiments, and implies a proposed connection of scientific Ideas with selected Evidence drawn from observations (Evidence → Ideas).

TLS2 also introduces experimental testing of students' pre-instructional conceptions. In particular, students' ideas on pressure variation with depth and density, which are in line with scientific concepts, are enhanced by experiments to be carried out by them. Proposed connections between CEI entities in such activities were discussed in the section 'The practices included in TSL1'.

A new type of activity is also implemented in TLS2, in which the teacher carries out lectures and demonstrations planned to induce cognitive conflict in the students. For example, the students are exposed to the following demonstration. They are asked to predict: (a) the relation between pressure in a wide and in a narrow vessel containing water to the same depth, and (b) the relation between the forces exerted to detach a narrow and a wide suction cup. Predictions about pressure and force based on the model of non-differentiated concepts (pressure–force model) are expected; that is, students are expected to claim either that these are equal or that the bigger the vessel/suction cup, the bigger the pressure or force exerted. The required predictions as to what will happen suggest the establishment of connections between students' alternative conceptions and the expected evidence (Ideas → Evidence). However, the experimental evidence that follows students' predictions is different: that is, equal pressures and unequal forces are observed. The aforementioned activity prompts the production of evidence from observations of pieces of the real world, which implies the connection of Cosmos to Evidence. What is important is that interpretation of evidence is based on students' alternative conceptions. The final selection of the appropriate scientific idea takes place during an extended whole classroom discussion, and is based on the epistemological principle of a concept being fruitful when it coherently unifies a class of phenomena.

Table 3. The practices included in TLS2.

Didactical proposal (with terms of activities)	*Cosmos → Ideas*	*Ideas → Cosmos*	*Cosmos → Evidence*	*Evidence → Cosmos*	*Ideas → Evidence*	*Evidence → Ideas*
A. Familiarization experiments			Observation of experimental evidence	Construction of experimental set-ups based on evidence from instructions Intervention on materials/set-ups based on evidence from instructions	Predictions of experimental evidence related to phenomena that will occur	Interpretation of experimental evidence
B. Classification activities						Connections of scientific ideas with selected evidence from observations
C. Testing ideas by guided experiment			Extraction of alternative evidence from raw data	Construction of experimental set-ups based on evidence from instructions Production of raw data based on instructions		Interpretation of experimental evidence

Table 3. (Continued)

Didactical proposal (with terms of activities)	*Cosmos → Ideas*	*Ideas → Cosmos*	*Cosmos → Evidence*	*Evidence → Cosmos*	*Ideas → Evidence*	*Evidence → Ideas*
D. Lecture – demonstration inducing conflict			Observation of demonstrated experimental evidence		Predictions of experimental evidence related to phenomena that will occur	Interpretations of evidence according to alternative ideas and selection of the fruitful idea according to the principle of unification
E. Discussion of new applications					Predictions of experimental evidence related to phenomena that will occur	Interpretation of evidence according to fruitful ideas

The final new teaching–learning activity includes extended whole classroom discussion of several new tasks aimed at demonstrating the fruitful application of the differentiated ideas of pressure and force. Students are asked to make predictions as well as to interpret evidence according to such differentiated ideas.

The wealth of connections proposed in TLS2 is demonstrated in table 3.

The results of the second TLS have shown considerable success with regard to students' conceptual learning; in particular, the differentiation of the concepts of pressure and force. As for the experimental skills concerned, no significant improvement was observed, since such skills were not targeted as a primary objective of TLS2 (Kariotoglou et al. 1993, 1995).

The practices included in TLS3

In the middle of the 1990s the researchers' interest shifted to elementary education student teachers at university, with limited knowledge of science concepts and procedures. Research data showed that these students' conceptual knowledge has similar features to those of 13-year-old to 14-year-old pupils, although it is richer in interpretations and terminology (Psillos and Kariotoglou 1999).

Table 4. The practices included in TLS3 over and above TLS2.

Didactical proposal (with terms of activities)	*Cosmos → Ideas*	*Ideas → Cosmos*	*Cosmos → Evidence*	*Evidence → Cosmos*	*Ideas → Evidence*	*Evidence → Ideas*
Open investigations to check previous classifications		Construction of experimental set-up relevant to hypotheses	Observation of experimental evidence		Construction of hypothesis	Interpretation of experimental evidence
Guided verification experiment of Pascal principle		Manipulation of experimental set-up and raw data production connected to ideas (Pascal)	Extraction of evidence from raw data			Interpretation of experimental evidence

TLS3 was addressed to these student-teachers, and is based to a considerable extent on TLS2. TLS3 includes types of activities quite similar to TLS2. Hence, for reasons of brevity, we focus our discussion on the new activities additional to those in TLS2.

The major change in TLS3 as compared with TLS2 is the equivalent pursuit of an understanding of scientific procedures in addition to conceptual knowledge. This bears a double justification: on the one hand, procedures are an inseparable part of scientific inquiry and, on the other, prospective teachers ought to become acquainted with this part of scientific inquiry as well. In this way, experimental activities are enriched and aim to facilitate not only conceptual, but also procedural understanding.

The new activities, which took place after familiarization, include first of all the designing of investigations by students themselves. Students are prompted to become involved in the planning and realization of experiments aiming at testing the variables affecting hydrostatic pressure in a liquid. This means that they are involved in the handling of hypotheses, the planning of experimental set-ups relevant to hypotheses and the observation of experimental evidence in the laboratory. The proposed connections are presented in table 4.

Furthermore, at the end, following lecture demonstration inducing conflict, the students attempt, through a guided experiment, the verification of a new law: that is, a regularity. The relevant experimental investigation concerns Pascal's principle, and uses a specially designed vessel fitted with three manometers and a syringe to increase pressure. What is important here is that students are asked in the worksheets to manipulate the experimental set-up and generalize beyond the evidence of the experiment to a more general description of the real world: that is, to attempt a connection Cosmos → Ideas.

The results have shown success in the conceptual domain, although the students followed diverse conceptual pathways (Psillos and Kariotoglou 1999). The objective concerning procedural learning proved to be less successful, largely due to a difficulty in handling theoretical concepts as entities of the material world, which would enable students to intervene in the experiments. For example, while pressure seemed to be understood by the students as a representation of the material world that is different from force, they were unable to handle it as an entity in order to intervene in an experiment. That is, students could not, when asked, intervene in an experiment concerning the Pascal principle, for example, and increase or decrease pressure (Kariotoglou et al. 1999).

Discussion and conclusions

In this paper we have proposed a framework for modelling didactical activities (epistemic dimensions) included in TLSs that draws on studies of scientific practice. We discuss here both the model and its fruitfulness as well as it application to the case of three sequences about fluids. We envision that several of the issues that are raised have implications for the design and analysis of TLS beyond this particular topic.

In this paper we have proposed a framework for modelling didactical activities included in TLSs that draws on studies of scientific practice. We discuss here both the model and its fruitfulness as well as its application to the case of fluids. We envision that several of the issues that are raised have implications for the design and analysis of TLS beyond this particular topic.

Following Hacking (1992), we suggest that the practices of scientific inquiry in diverse settings are characterized by the kinds of connections among entities perceived within the adopted framework, which in our case involve three categories – namely Cosmos, Evidence, Ideas – as well as by ways of connecting these categories. We argue that such a framework has one important advantage; namely, the capacity to describe the activities of laboratory sciences in diverse settings, like the pursuit of actual scientific inquiry in professional settings or the pursuing of scientific inquiry by students in educational settings.

Concerning educational settings, the employment of such a three-level model has the advantage of allowing a fruitful modelling of teaching–learning activities in terms of scientific practice, which is equivalent to an epistemologically clear representation of teaching–learning interactions, not often appearing in published works. We consider that it is possible to distinguish planned teaching–learning activities in a TLS either as related to interventions onto the material world on the basis of an idea or specific evidence (i.e. connecting I → C or E → C) or as representations of the material world (i.e. connections like I → E, E → I, C → I or C → E). We suggest that such a distinction is didactically fruitful both for the analysis and the planning of activities, since it makes it feasible to detect activities within a TLS in which interaction between the human and the material factor prevails and to distinguish them from those in which human interaction dominates.

We may note, too, that the CEI model is at once general and generic. In other words, the model refers to all the entities involved in each of the three categories without specifying particular interactions among specific entities. These may be brought out at a more concrete level by inserting specific entities into each category. Such a potentially fruitful work is beyond the scope of the present paper, which aims at characterizing the overall evolution of the practices in all successive TLSs on fluids.

Application of the CEI model for the description of didactical activities included in the set of TLS on fluids resulted in the distinction of diverse proposed practices regarding the pursuit of scientific inquiry. In the initial official curriculum on fluids, the pursuit of scientific inquiry is mainly restricted to the representation level. Ideas are connected mainly with Evidence, which is selectively drawn from Cosmos, aiming almost exclusively at the interpretation of Evidence. The official Greek curriculum is characterized by a lack of intervention practices: that changes in all the subsequent TLSs, which emphasize diverse patterns of laboratory work by students. A considerable number of connections between Evidence and Cosmos are attempted, such as constructions of experimental set-ups and production of raw data based on instructions (Evidence → Cosmos) or extraction of evidence from raw data (Cosmos → Evidence).

At the representation level, in TLS1, TLS2 and TLS3, connections between Ideas and Evidence are gradually multiplied in both directions. Moreover, there is a variety of activities leading to a considerable enrichment of links between Ideas and Evidence in TLS2 and TLS3 as compared with TLS1. Some remarks follow. In effect, a long-term persistent empirical endeavour to develop rich didactical activities regarding one particular topic progressively leads to the materialization of links that are anticipated by CEI. We consider this fact as evidence for the validity of the model. Besides, the enrichment of activities points to a conception of the TLS as a generic tool in which the designed combination of craft knowledge with theoretical modelling may lead to potentially rich student activities adaptable to multiple settings

On the basis of the aforementioned analysis, we may claim that, as the TLSs evolved, on the one hand the number and direction of proposed connections among the categories of Cosmos, Evidence and Ideas increased, and on the other, these connections were promoted by enriched multiple activities. We may note here that TLS1 was developed when discovery was the dominant approach to science teaching, while TLS2 and TLS3 are based on constructivism (Kariotoglou et al. 2003). In other words, in the more elaborate TLS3, developed under the influence of the new constructivist perspectives in Science Education, students have the possibility of engaging in rich scientific practices relevant to scientific inquiry. Figure 2 depicts the relative importance attributed to each CEI interaction in the official curriculum and the three TLSs. The width and colour of the arrows suggests the variety of activities leading to enriched connections between Cosmos, Evidence and Ideas. The figure includes also the initial official curriculum as well as proposals for revising TLS3 towards TLS4, depicted in dotted lines since it has not yet been applied, as discussed later.

Tables 1–4 and figure 2 reveal that, although the practices included in TLS1, TLS2 and TLS3 were gradually enriched, they still fall short in the area of connections that concern the direct linking of the material world with the world of ideas. Such a link is partially feasible only in TLS3, where understanding of

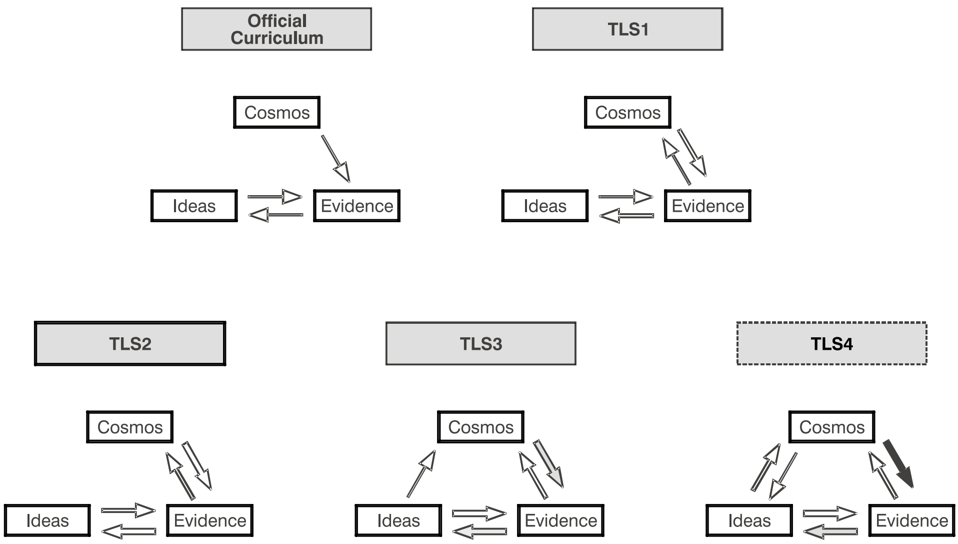

Figure 2. The enrichments of practices in the TLS on fluids.

scientific procedures is pursued by activities involving the designing of experimental investigations by the students themselves. As matter of fact, only two activities regarding I → C practices were identified in TLS3. The first concerned the construction of an experimental set-up by the students in order to check a hypothesis; in the second, students were asked to handle the Pascal apparatus (see figure in appendix 1) in terms of pressure (i.e. to increase pressure inside the liquid). They were both I → C practices not C → I ones.

This being the case, we envision the evolution of TLS3 towards TLS4 by proposing additional activities that would potentially lead to practices promoting enriched connections of the kind Ideas → Cosmos and vice versa. Moreover, we argue that the possibility of extending a TLS and planning new activities shows that the CEI model, apart from offering an *a posteriori* representation of teaching–learning activities in terms of scientific practice, may be also employed for monitoring the kinds and directions of links between entities, and thus leading to the design of appropriate new activities. In appendix 1, we present in some detail an example of guided laboratory work on the Pascal principle in order to illustrate such a design proposal.

We consider that the new possibilities offered by the CEI model as already exemplified are indicative of its productive power as a tool allowing the design of new didactical activities in order to enrich TLSs. In particular, if a comparison is made in terms of the CEI model between the students' framework of everyday ideas and that of the scientific Ideas to be taught, we may reach the following conclusion: students are very good at handling their everyday ideas in the frame of C → I or I → C practices. For example, they are able to intervene effectively and directly on at least some parts of the material world, by using their everyday idea of the connection between force and motion, or the non-differentiated concept of pressure/force. Accordingly, we argue that teaching proposals attempting to promote scientific inquiry may not be effective in addressing learners' views, if they do not make direct links between I →C and C →I, but instead make these links indirectly via I → E → C and C → E → I activities. In such a case, students' initial views regarding the relationship between Cosmos and scientific Ideas would still be considered by them as more fruitful and thus would dominate over the Ideas to be taught. The eventual failure of the teaching to make the direct links I → C and C → I might provide another explanation why the persistent learning of scientific Ideas is so hard to achieve.

In conclusion, we consider that the descriptive and productive capacities of the CEI model, as exemplified from its application on the *a posterior* examination of the historical evolution of a series of TLSs on fluids, revealed important common and differential features affecting their development.

Attempting a generalization in the context of the discussion on designing TLSs, we consider that it might be important for a TLS on a topic originating from laboratory sciences to include students' activities aiming at achieving all possible connections between the entities from the categories of Cosmos, Ideas and Evidence. This proposal arises from the position that the CEI model can describe in common terms aspects of the pursuit of scientific inquiry in diverse settings, including professional and teaching contexts. Therefore, such a proposal would be based on the assumption that the didactical transformation of the scientific knowledge can and should conserve the epistemological features of the scientific knowledge and procedures taught, as represented by Hacking's realistic approach, which, let it be noted, is not in conflict with Kuhn's constructivist point of view (Hacking 1995: 65–71).

Our proposal, stemming from the epistemologically based CEI, points out where the desired connections between Cosmos–Evidence–Ideas should be pursued in a TLS, provided that the connection between the literal–representational aspect of scientific knowledge and the practical–interventionist aspect are included in the aims of science education as perceived by the designers. As to how such connections would be made effective, our analysis revealed that enriched intervention and representation activities were realized in the constructivist-based TLS, which we believe holds as the present dominant approach to science teaching and learning. Certainly, detailed proposals on the grouping and time succession of activities need specific extended discussion for each TLS, and this is beyond the focus of the present paper. We may envision, however, taking into consideration recent discussions in the science education community, that social constructivist approaches would be beneficial in the case of activities in which human interaction dominates, as mentioned according to the CEI formulation; while on the other hand, for activities in which interaction between the human and the material factor prevails, individual (cognitive) constructivist approaches would prevail.

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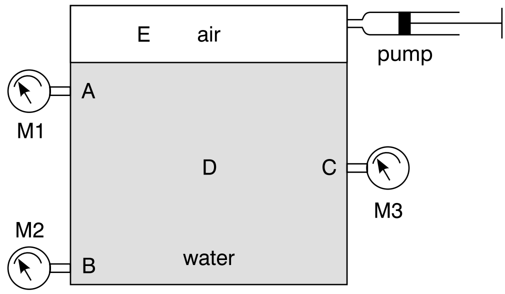
Appendix 1: an example of envisioned additional labwork to be included in TLS4

We assume that the laboratory Cosmos in such a piece of labwork consists mainly of a laboratory apparatus functioning according Pascal's law, as in the Figure below.

The apparatus consists of a closed transparent vessel containing water up to a certain level and air above that level. Three electronic manometers M1, M2 and M3 are fitted at three different levels on the vessel. Finally, an air pump is fitted at the top of the vessel, as in shown in the figure.



A starting activity that could challenge students' views regarding the relationship between data and evidence, which can be described as a practice of the kind C→E, could be taking readings from manometers M1, M2 and M3 and using them to make estimates of the pressure at points A, B, C, D and E. If, in addition, students are asked to justify their responses, then they may be motivated to develop more practices in order to justify their decisions (which may also require linking them with their existing views about pressure and its distribution in the vessel.), especially regarding the estimation of pressures at point D and E. Accordingly, students are guided to investigate the Pascal principle in line with TLS3 activities

As new activities for TLS4 could follow a series of intervention activities on the apparatus, based on the application of the scientific concept of pressure and/or students' existing views regarding the distribution of pressures in the vessel, aiming at enhancing linking practices of the type I→C. We argue that this specific type of practice is generally absent from typical labwork. This has the important effect of concealing the powerful intervening aspect of scientific Ideas (I→C), thus exposing only their representational (interpretative and predictive) nature (E→C and I→E). For example, we could ask students: to manipulate the apparatus in order to increase pressure at point A (intervention on the Cosmos guided by the Ideas of students regarding pressure variations); to decrease pressure at point B without altering pressure at point E (intervention on the Cosmos guided by the pupils' Ideas regarding pressure variations in and out of the water); to increase pressure difference between points B and C (intervention on the Cosmos guided by students' Ideas regarding pressure variations in the water).