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Laboratory activities, science education and problem-solving skills

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Abstract

Science education specialists, science teachers as well as Portuguese science curricula acknowledge lab activities as important educational tools, namely for students to learn how to do science. If doing science is conceptualized as solving problems, some kinds of lab activities may be more appropriate for students to attain that objective than others. This paper presents a categorization of lab activities based on both their main educational goal and the way they deal with phenomena and models. Afterwards, it discusses the extent to which each type of lab activities fosters the development of problem-solving skills.

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Keywords: laboratory activities, science education, problem-solving, problem-based learning

1. The role of lab activities in science education

The Portuguese science curricula guidelines (DEB, 2001) as well science teachers (Abrahams, 2011; Leite & Dourado, 2007) and science education specialists (e.g., Hofstein, 2004; Millar, 2010; Wellington, 2002) acknowledge laboratory activities (also known as lab activities) as important educational tools. Over the years, several arguments have been put forwards for the use of lab activities in science education. One of them has to do with a particular interpretation of the following Chinese saying: tell me, I'll forget; show me, I'll remember; involve me, I'll understand. 'Involve me' has been understood in a restrict way, that is ask me to do things in the lab, with lab apparatus, reactants, and so on, ignoring or at least not valuing thinking about what happens in the lab. Of course people can forget what they listen to and they may remember what they watch but this raises a question: what do they remember from the scene? Is it the visual and/or spectacular part of the activity or is it its meaning? And when they do practical things themselves (so that they are immerse in the scene) based on a

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screenplay-like worksheet, then what guarantees do teachers have that they understand the scene they are playing? Is handling apparatus enough to yield understanding?

Another argument has to do with the idea that "science is practical". A belief in this argument leads to the idea that if scientists use research laboratories to develop theories, then students should use school science laboratories to learn them (Jenkins, 1999). It would also mean that students should rediscover the science content prescribed in the curriculum. The question is how long would it take and what guarantees would teachers have that they would discover the same as past scientists did?

Hodson (1988) argues that science education includes three major components that are worthwhile being conceptualized to be differentiated, as they require different teaching approaches, being some more lab based than other do. Those components are: learning science, learning how to do science and learning about science. According to Hodson, lab activities are not required for students to learn the science content that was discovered by past scientist neither to learn about the nature of science. In the former case, it should be emphasized that lab activities show what happens; they do not show why it happens (Woolnough & Alsop, 1985). Even if lab activities are used, teachers have to find effective ways of dealing with the 'why', that is of teaching science content without having students rediscovering what scientists have already discovered. As Einstein and Infeld (nd) have argued, concepts are free creations of the human mind, and are not uniquely determined by experiments, even though the opposite may seem to make more sense at first sight. These are the reasons why Millar (1998) argues that if we teach science because it is a practical subject, we also teach science because science is a theoretical subject. In fact, there is no previously known path that leads directly from an experiment to a new theory. Rather, there is a complex interplay between theory and practice (Leach, 1999), that is schematically represented in figure 1 (translated from Leite & Figueiroa, 2004). An implication of this interplay is that one observes what his/her theories 'show' him/her and one does the experiments that his/her theories allow him/her to do. This is so because empirical evidence serves as a basis for new ideas development and at the same time it depends on the ideas that yield it (Hodson, 1988; Ball, 1999). Therefore, not only creativity, imagination and insight, but also disappointment, difficulty, success and failure are typical steps of an explanation building process (Jenkins, 1999). Hence, students could conceptualize things differently from the way scientists do.

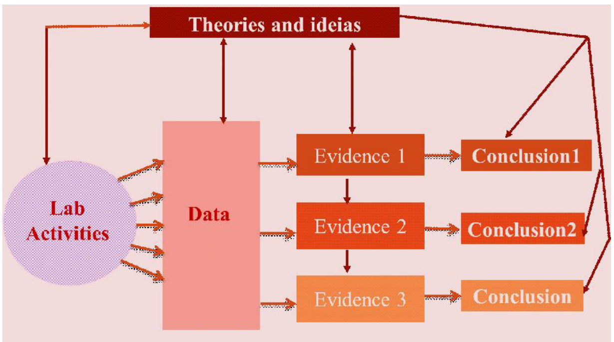

Figure 1: Interplay between theory and evidence

As far as learning about science is concerned, it is worth noticing that no science theory development path can be easily and rapidly replicated or modelled in a school science laboratory. Thus, Hodson (1994) believes that instead of having students working in the laboratory, it is worth having them doing an analysis of the history of some science ideas. This would lead students to perceive how science knowledge evolved as well as how its evolution was influenced by technological, historical, political, social, etc. factors and caused itself modifications in technology, society and environment.

However, Hodson (1994) also argues that lab activities are required if students are to learn how to do science.

This science education component requires the mastery of some basic skills, processes and methods that need to be learned by doing (De Pro, 1998). However, learning them 'one by one' is not enough for learning how to do science. In addition, this is not consistent with the practice of receipt-like lab activities, which Hofstein and Lunetta (2004) found that have pervaded science teaching over the last decades. To some authors, the point is that learning how to do science requires students to acquire a flavour of what doing research means. Thus, although research results are not completely consistent (Sadler, Burgin, McKinney & Ponjuan, 2010), some authors argue (Bleicher, 1996; Ritchie & Rigano, 1996; Schwartz, Lederman & Crawford, 2004) that this component can be better developed in research laboratories. Nevertheless, it is worth mentioning that throughout decades several authors (e.g., Bennet, 2001; Caamaño, 1992; Kerr, 1963; Kirschner & Huisman, 1988; Woolnough, & Allsop, 1985) have put forwards lists of educational valuable objectives that may be attained through school lab activities. Those objectives were summarized by Hodson (1994), as follows:

- To foster students' extrinsic motivation for learning science;
- To develop scientific attitudes, that is attitudes that scientists are supposed to have (e.g., critical thinking, probabilistic thinking, objectivity, persistence);
- To develop content knowledge, related to understanding and using science concepts, laws, theories;
- To develop lab skills, including mastering lab techniques and handling equipment as well as potentially harmful materials safely;
- To become familiar with science methods, including doing problem-solving and using data to build empirically based arguments.

This list raises three different issues. One of them has to do with motivation. There is some evidence that lab activities may motivate students and develop students' attitudes towards science (Abrahams, 2011). However, the fact is that on one hand all activities' that are carried out in science classes should motivate students and, in the other hand, according to Ausubel, Novak and Hanesian (1980), extrinsic motivation is limited in terms of its educational value. Therefore, yielding motivation should not be the only motive why lab activities are carried out. The other one has to do with the fact that the development of scientific attitudes should be ever present, in lab as well as in non-lab classes. The third one has to do with the fact that lab activities performed in schools may hardly help students to attain those objectives. As a matter of fact, teachers and even some curriculum guiding documents hardly differentiate among some basics concepts associated with lab activities which may impair students from benefiting from lab activities as they should. In addition, it may lead teachers to think that as far as they have students doing lab activities, they have students learning how to do science. Unfortunately, this is not the case (Hofstein & Lunetta, 2004). Therefore, some conceptual clarification is needed in order to help making sense of the requirements that school lab activities may have in order to play a meaningful role in science education, namely with regard to doing science.

2. From practical work to lab activities

Practical work, lab work, lab activities, lab experiments and investigations are some related but different concepts that are worthwhile defining so that lab activities are used in a more rational way. Hofstein and Mamlok-Naaman (2007) argue that to support science education knowledge development (by informing curriculum development, teaching and assessment practices, and education policy), "it is essential to define technical terms precisely to explicate knowledge in the field [and] to use those terms consistently in research reports and in scholarly writing." (p.106). Thus, differentiating among lab work related concepts is a necessary requirement for increasing the probability of having students to effectively attain the diversity of objectives referred to above.

Thus, practical work has to do with all the practical activities that require students to be actively engaged (Hodson, 1988), from a cognitive point of view. It may include lab activities (LAs) as well as paper and pencil activities, field activities (FAs) or other sort of activities. Lab work encompasses all the lab activities that students do. Lab activities have to do with things like the study of natural world from their indoor reproduction, the analysis and/or discovery of the underlying structure or material composition of some object or natural sample. They require that usual lab materials or alternative materials are available and used. They can take place in the school science laboratory or in a normal classroom (if no specific safety requirement has to be taken into account). Experiments (E) have to do with activities that require control and manipulation of variables. If, in addition, they involve lab activities, than they are a special part of lab activities and are encompassed by the lab work concept too. However, they can rather involve field activities, computer based activities, etc., and they can, therefore, be non-lab activities (nLAs). Finally, investigations (I) are problem-solving activities that are not supported by a worksheet. As a matter of fact, problem-solving activities face students with a dilemma that they feel as worthwhile solving (Jonassen, 2004). This dilemma is associated with a felt need that is perceived as worth to be fulfilled. Thus, investigations may be lab-based investigation activities (LI) if they require the performance of lab activities, but there are other types of investigations, which can take place, for example, in the social or natural field, or in a computer. Figure 2, taken from Leite (2002a), shows how the different types of activities relate to each other.

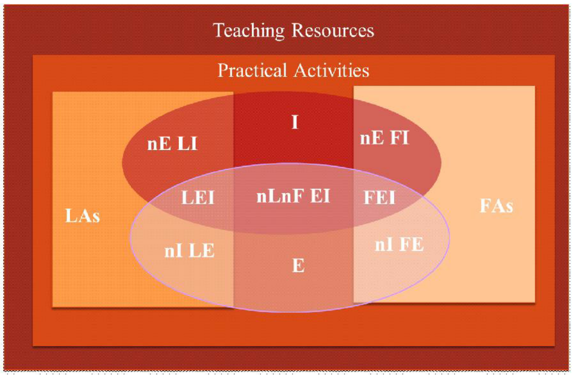

Figure 2: Relationship among several lab activities related concepts

The main purpose of lab activities is to help students to make links between the domain of real objects and the domain of ideas (Millar, Tiberghien & Le Maréchal, 2002). However, there is often a mismatch between intended and achieved students' learning outcomes (Psillos & Niedderer, 2002; Woolnough, 1998), as the latter depend on the very specific things students do and the way they do them. On the other hand, it is well known that teachers are highly dependent on school textbooks with regard to what they do in the classroom (Tobin, Tippins & Gallard, 1994; Morgado, 2004), namely in what concerns lab activities they use in their science classes (Leite & Dourado, 2007). The point is that school textbooks do not make such differentiation and therefore they do not facilitate teacher's job of providing students with a diversity of lab activities, selected according to the outstanding learning objective they want students to achieve. As a matter of fact, research has shown that a considerable amount of lab activities included in school science textbooks or laboratory guides (Bandiera, 2002; Galiana, 1999; Hofstein & Lunetta, 2004), namely in the Portuguese ones (e.g., Dourado, 2010; Figueiroa, 2007; Leite, 2002b; Leite, 2006; Sousa, 2009), have a low level of openness, provide data and their interpretation, aim at confirming previously introduced content knowledge or to obtaining the right answer, do not ask students to collect data that would be evidence of the required conclusion, do not use an appropriate control of variables, etc. This means that they miss relevant educational characteristics, namely at the epistemological level and in some cases they even suffer from a lack of internal consistency which prevents students from making sense of what they do or what they get from them.

3. Classifying lab activities

For a long time, several authors have classified lab activities. When they do it, they usually focus on conceptual and procedural issues. Some authors suggested a reduced number of types of lab activities (e.g., White & Gunstone, 1992; Woolnough & Allsop, 1985) and others used a lot of types (e.g., Caamaño, 1992; Wellington, 2002, Roberts, 2004). The classification criteria differ from study to study and in some cases they are not completely explicit. These ambiguities make it hard to make sense of the relative educational potential of lab activities, namely in terms of students' expected roles and learning outcomes. As a matter of fact, several criteria can be used to classify lab activities, each of them leading to a set of types of activities. However, criteria should be intelligible, useful and relevant. The most relevant from an educational point of view are: responsibility of the performance of the lab procedure; object of study; and outstanding learning objective. An appropriate use of these criteria requires a previous analysis of the broad structure of a lab activity. Besides, it should be noticed that doing lab activities includes performing a procedure - the lab phase - but lab activities are not limited to that. In fact, two other phases should be considered: the pre-lab phase, devoted to the theoretical preparation of the laboratory phase, and the post-lab phase, that is targeted to the analysis and discussion of lab results. Nevertheless, the pre- and post-lab phase may be more important within the context of one type of activity than in the other, depending on factors like the outstanding objective of the lab activity, the way it is integrated in the teaching sequence and the expected engagement of the student in the data analyses and interpretation processes.

Thus, based on the criterion centred on who assumes the responsibility of performing the lab procedure, lab activities can be classified as lab demonstrations or as students' lab activities (Millar, Tiberghien, & Le Maréchal, 2002). In the former case, students just observe someone (usually the teacher) performing the lab procedure; in the second case students perform the lab procedure themselves, either individually or in small groups. It should be noticed that the performance of the procedure makes a difference in terms of procedural learning, but it does not mean that students learn less or worse than if they were performing the procedure themselves. In fact, there is some evidence that demonstrations may be effective (Gaspar & Monteiro, 2005; McKee, Williamson & Ruebush, 2007) or even more effective (Couto, 2000) than students' activities, at least with younger students, when learning science is at stake. These results may have to do with the fact that younger students have more difficulty in working and thinking systematically than their older counterparts. Besides, the pre- and post-lab phases may help student to make sense of the procedure they observe someone else performing. During the performance of the procedure they can also be cognitively engaged with what is going on, as far as teacher discusses with them what is being done.

With regard to the object of study, lab activities can focus on a phenomenon that is reproduced in the lab to be better understood or on the mechanical modelling of an entity, whether to understand how it is or how it works. As far as the outstanding objective is concerned, it has to do with the distinguishing learning outcomes that a given activity enables students to achieve when compared to the other lab activities. In fact, there are several competences that students can develop whatever the kind of lab activity but there are some that can be better developed from one type of lab activities than from the others. These two criteria can be combined so that activities can be classified according to both. Nevertheless, activities that focus on understanding reproduced phenomena have outstanding objectives that differ at least in part from the objectives of the modelling ones. Therefore, activities having one of these focuses will be categorized separately, based on previous work done by Leite (2002a) and Dourado and Leite (2008).

Table 1 (based on Leite, 2002a) shows the types of lab activities focusing on reproduced phenomena that result from the use of the outstanding objective criterion. The outstanding objectives focusing on conceptual knowledge indicate how and when the lab activities can be used. In fact, lab activities aiming at reinforcing conceptual knowledge require concept teaching to happen in advance that is before the lab procedure is put into practice; those targeted to knowledge construction require concepts to appear after the lab procedure is carried out; those aiming at knowledge reconstruction require students' ideas to be elicited during the pre-lab phase and the accepted ideas (if different from students' ideas) to be introduced in the post-lab phase. Even though lab skills and technics may be developed within other types of activities are carried out, mastering them with proficiency requires explicit learning and training (Woolnough & Allsop, 1985; De Pro, 1998). Therefore, lab skills and technics oriented activities are a sort of pre requisite for other activities. However, they should be included in a meaningful context that is they should be used when the technics or the skills are required for other purposes. Finally, it should be stressed that investigations are the only type of lab activities that has two broad outstanding and different objectives, namely conceptual and methodological objectives. In fact, they enable students to learn conceptual knowledge at the same time as they develop science methodology related competences. They are also integration promoting activities as they require students to use conceptual and procedural knowledge to draw and put into practice a procedure that they find appropriate to solve the problem given in the activity statement.

Table 1. Types of lab activities that focus on phenomenon reproduction, based on their outstanding objective

Outstanding objective		Type of Lab Activities	Brief description of what students have to do
Lab skills and technics mastery		Exercises	Carry out a technique or use some equipment repeatedly in order to acquire training
Conceptual knowledge	Knowledge reinforcement	Activities for getting a feeling of the phenomena	Smell, listen, touch, watch just to get a feeling of how it looks like
		Illustrative activities	Get a confirmation of some idea that was already taught to make sure that it is like that
	Knowledge construction	Activities to find out what happens when…	Follow a receipt like worksheet in order to get "the right answer", that is the only possible answer if everything works properly
		Investigations*	Discover new knowledge on his/her own by solving a problem; no worksheet is available
	Knowledge reconstruction	Preview-Observe- Explain-Reflect, procedure given	Follow a pre lab, lab and post lab procedure thought able to originate cognitive conflict and to foster a conceptual change process
		Preview-Observe- Explain-Reflect, procedure not given	Draw a procedure thought able to originate cognitive conflict and to foster a conceptual change process
Scientific methodology development		Investigations*	Draw a strategy to solve a problem, put it into practice and conclude; methodological and conceptual knowledge are developed

* the same activity serves both objectives

Table 2 (adapted from Dourado & Leite, 2008) shows the types of lab activities dealing with mechanical modelling that result from the use of the outstanding objective criterion. Their outstanding objectives range from the less demanding ones, centred on visualizing models without interfering with them, to the most demanding ones, focusing on building up a model which is thought to correspond to a part of the world that is under study.

In fact, models are representations of reality that are thought to describe it (Gilbert, Boulter & Rutherford, 1998; Justi & Gilbert, 2002) but that cannot be taken as true, in absolute terms, because they are used when the entities to be studied through modelling are non-accessible (due to its large dimension, to the time they take or to the distance people are from them). Therefore a model cannot be directly compared to the reality it is supposed to describe. Of course as students may not have the chance of observing the reality, then they may feel it difficult to accept model-based lab activities (Sensevy, Tiberghien, Santini, Laubé & Griggs, 2008; Tiberghien, 1999).

It is worth emphasizing that most of the types of activities given in tables 1 and 2 may be either performed by students or demonstrated to them by the teacher. However, activities for getting a feeling of the phenomena (table

1) need to be performed by the students themselves so that they can get that feeling. Similarly, investigations (table 1) and development of a model activities (table 2) should to be performed by the students because they have procedural knowledge related outstanding objectives.

Table 2. Types of lab activities that focus on mechanical modelling, based on their outstanding objective

Outstanding objective	Type of activity	Brief description of what students have to do
Perceive underlying mechanical models	Visualization of a statics mechanical model	Students have to observe and describe a structure that does not change over time in order to find out how it is
	Visualization of a dynamic mechanical model	Students have to describe structure that changes over time in order to find out how it is. The modification conditions belong to the model and cannot be altered.
Understand underlying mechanical models	Exploration of a mechanical model	Students interacts with a model of a changing phenomenon in order to study how it behaves under different conditions
Discover an underlying mechanical model	Development of a mechanical model	Student has to discover and to build up a model of a phenomenon or structure based on an analogy with some familiar situations or without any support. It promotes knowledge integration as well as problem solving and modelling competences. It shows how it is, how it works and it behaves.

4. Lab activities and problem solving for problem-based learning

Although there is no single way of doing science (Woolnough, 1998), science is about “solving problems, be that to create new knowledge, to answer empirical questions, to make something or to make that something work.” (Roberts, 2004, p.115). In addition, solving “problems with no easily recalled solutions, is the ‘ideal goal’ of practical work” (Roberts, 2004, p.119). Hence, Woolnough (1998) states that problem-solving activities should be included in the science curriculum in order:

- to enable students to develop and use personal knowledge;
- to enable them to experience doing authentic science;
- to provide students with the skills and attitudes that are useful to employees;
- to motivate students towards science and to learn science.

Taking these objectives as reference, an analysis of tables 1 and 2 shows that only a reduced part of lab activities have to do with problem-solving, as it was defined in section 2. As a matter of fact, only Investigations (table 1) and Development of a mechanical model (table 2) activities can give students the opportunity to use personal knowledge and to experience doing authentic science. Their holistic nature requires an integrated use and development of conceptual and procedural knowledge. If they are contextualised in everyday situations, then they may also promote both students’ intrinsic motivation to learn science and development of skills and attitudes. Everyday contextualization of these types of activities would favour transferability of competences and make them more useful in work contexts. Nevertheless, as Roberts (2004) puts it, investigations are in no sense in competition with other types of lab activities: “one type is no better than another. They complement each other” (p.119) in the sense that some specific competences developed through close lab activities (like exercises or vizualization of mechanical models) may be needed by problem-solving activities while the latter give meaning to the former, as close activities are better conceptualized as a mean to a useful end.

Drawing appropriate problem-solving strategies requires conceptual and procedural competences (Roberts, 2004) that may either be mastered in advance or be learned at request for problem-solving to reach a successful end. However, “Contemporary research and theory on problem solving argue that problem solving skills are domain and context specific, that problem-solving activities are situated, embedded, and therefore dependent on the nature of the context or domain." (Mukhopadhyay, 2013, p. 21). Therefore, problem-solving competences should not be expected to be easily transferred from one context or content to another one, different from that in which they were first developed. However, success on learning as well as on transferring acquired knowledge is also dependent on students' prior knowledge as well as on affective factors (Toh, 1991).

Problem-solving is related *to* but different *from* problem based learning, as the latter requires the former but the opposite is not true. Problem solving can be done at different pedagogic moments (Leite & Esteves 2005). It is often done after teaching, as an opportunity of using previously acquired knowledge. For example, after studying about the structure of animal and vegetal cells students can be asked to identify the origin of a piece of live material, based on cell structure. Such an activity would not lead to new conceptual knowledge but it may reinforce and stimulate the integration of previously acquired knowledge. However, problem-solving can also happen during teaching, as a way of getting feedback about how learning is taking place and as a strategy to deepen some aspects of it. For example, after studying some separation techniques, students may be asked to identify the components of an aqueous mixture of substances in order to perceive that naked eye observation is not enough to be sure that all components were separated from water – it may happen that some colourless substance dissolved in the water is left. Solving this problem would give teacher feedback on whether or not they are able to use the recently learned separation techniques and would enable him/her to make students feel that those technics have some limitations. Therefore, it can lead to further development of conceptual knowledge.

Finally, problems can be used as starting points for learning which is the most innovative way of using problems. It has to do with problem-based learning (Lambros, 2004) that is a student centred teaching approach that enables students to acquire new conceptual knowledge by solving problems. Hence, students can be asked to work on a problem as if they were scientists, and to try to solve it. To do so, students have to analyse the problems in order to find out what they have, what they need to know and what they need to do to find an answer for the problem (Lambros, 2004), assuming that at least one solution does exist. Then they have to look for conceptual information and/or for lab techniques in order to draw appropriate lab procedures to reach the solution. If this does not work, everything has to be revised so that a happy end is reached.

Investigations can be used for problem-based learning purposes given that they are organised around a dilemmatic issue (problem) that is felt as a need that is worth being fulfilled. A problem may be brought by the teacher or by the students or it may emerge from a scenario. In any case, to be consistent with PBL the problem has to be solved by the students, preferably in small groups. If problems or scenarios are brought by the students, then they may be harder to fit a prescribed curriculum than the teacher brought ones are. Mechanical model building activities (table 2) also fit the requirements of Problem-based learning even though they may be more demanding and time consuming than investigations are. In fact, they require a problem solving strategy to be drawn (being conceptual and procedural knowledge required for that) and technological knowledge to be used. In fact, students may have to conceptualize the model and afterwards they have to construct and test the mechanical model for its fit with the observed evidence. The model has to be improved so that the best fit is achieved. A good mechanical model would be the one that leads to observations that are similar to those observed in the real world, in the place modelled. Hence, differentiating among lab activities shows that some of them (investigations and development of a mechanical model) may be problem-solving activities. In addition, these activities may also be used as starting points for learning, within a problem-based learning framework. Distinguishing the conditions of implementation of the lab procedure from the overall structure of the activity enables to understanding that handling equipment does not necessarily means that students are doing investigations even though it does not make too much sense inhibiting students from handling equipment and carrying out the lab procedure when they asked to draw the procedure themselves within an investigation activity setting.

5. Final remarks

Science is about solving problems. Some problems can be solved in the lab but the school science lab has not been used as an appropriate context for students to learn how to do science. Problem-based learning has shown to be a promising approach for learning conceptual as well as procedural knowledge. It may also provide opportunities for students to learn how to investigate (Hofstein & Lunetta, 2004) in order to solve real world problems and, in doing so, to relate science to technology and society (Llorens-Molina, 2010). Solving a problem in science requires a synthesis of two sets of understandings: a substantive understanding and a procedural understanding (Roberts, 2004, p.115). Using a problem as a starting point for learning a certain content may require more time than if the content was taught through a teacher-centred approach. Thus, it is obvious that pupils will not be able to do many problem solving activities in an overcrowded curriculum (Roberts, 2004). However, it is worth keeping in mind that when students solve a problem, they develop a lot of other competences besides the concepts required by the problem. In addition, students' difficulties with PBL decrease with experience (Ünal & Öxdemir, 2013). This means that teachers need to perceive that students need time to get acquainted with problem-based learning and to believe that students may learn without being told the content.

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