EXPERIMENTS AND MODELS FOR PHYSICS LEARNING IN PRIMARY SCHOOL

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Abstract

The project "Little scientists in the lab: Experiments & Models for science learning in primary school", funded by the Ministry of Education and currently under development and designing in Italy, is addressed to primary school teachers and to pupils. It proposes a "Model-Centered Learning Environment" of pilot activities for teaching and learning Physics and Sciences, based on experiments and modelling. A website supports teachers' school activities, facilitating and promoting communication and exchanges of materials between teachers and researchers of the University of Modena and Reggio Emilia, as well as between teachers themselves. In this paper, we illustrate the general features of the project and focus on preliminary results of a training intervention for in-service teachers on fluids and electricity.

1. The project "Little scientists in the lab: Experiments & Models for science learning in primary school"

The project aims at designing and testing innovative ways of teaching Physics and Science in primary schools. It promotes the exploration of curricular subjects employing elementary models. Its pillars are teachers' training and follow up activities, targeted on supporting lesson planning.

Teachers' training paths are designed to provide a model-oriented teaching and learning system. They are based on laboratory activities, modeling and content-specific knowledge using a cooperative learning method. Such an approach is inspired by the Karlsruhe Physikkurs (KPK) (Hermann, 1995) and by the Continuum Physics Paradigm (Fuchs 1997a; 1997b; 1998). From this point of view, we offer to primary school teachers an opportunity for training in Physics focusing on elementary concepts and models (Hestenes 1997, Gilbert & Boulter 2000) and constructing a shared language. These concepts are recurring in curricula and cross all scientific disciplines. They are key to exploration and understanding. Teachers should then plan and carry out their classroom teaching actions autonomously. A website and specific training support their everyday activities to prepare didactical pathways. Experimental and multimedia materials, which have been tested during the training courses, are available for teachers to be used as teaching tools in class.

For in-class activities, the project supplies 3 integrated tools: i) animated stories to boost motivation, with a character named Leo; ii) Leo's case, containing a set of didactical tools to carry out experiments under the teacher's guidance; iii) modelling tools (software, cards, drawings, role games) to promote thought and further discussion. These tools are integrated as follows: the teacher shows in class one of Leo's animated stories, then guides students to design and perform experiments with the help of the materials included in the case, and finally leads the students to discuss the experimental activities performed.

In the following chapters, we will describe, as an example, a training intervention for in-service teachers on fluid and electric circuits. The key is presenting analogy to teachers as a way to move from a familiar context, problem or domain, to a related unfamiliar one (Gentner D. & Gentner D.R.,1983; Reeves L.M., Weisberg R.T. ;1993; 1994). Thus, we suggest, as other authors have investigated, (Black & Solomon, 1987; Van den Berg & Grosheide, 1993; Cosgrove, 1995; Heywood & Parker, 1997; Paatz et al. 2004; Chiu & Lin, 2005) the use of analogy to pass from the fluids context to electricity.

We will analyze teachers' results in terms of the elementary models employed and difficulties encountered. Finally, we will focus on some preliminary topics emerging from such an approach.

2. In-service teachers' training

Scientific knowledge must be actively built up by the learner (Driver et al. 1994). In this process, the teacher's role has important elements. One of these "is to introduce new ideas or cultural tools where necessary and to provide the support and guidance for students to make sense of these for themselves" (Driver, 1994). Research has investigated teachers' elementary ideas on Physics topics (Shipstone et al. 1988; Kruger, 1990; Kruger et al., 1992; Webb, 1992; Greenwood 1996; Stocklmayer & Treagust, 1996; Atwood et al. 2001; Heywood & Parker,1997; Testa & Michelini, 2006), showing that they often share the same alternative conceptions as their students.

For these reasons, our training strategy is centered on putting teachers in the same situations (i.e. laboratory and modelling activities) they could offer to their students (Pontecorvo et al., 1987;

Leinhard, 1988; Chaiklin & Lave, 1993). Teachers directly experience questions, difficulties and urges of their students and can experience the effective advantage of training activities.

According to the literature, students' alternative frameworks and reasoning schemes about electric circuits can be briefly catalogued as follows: current is consumed when passing through a resistance (Tiberghien, 1984; Shipstone et al., 1988; McDermott & Schaffer, 1992); current provided by a battery is independent of the circuit topology (Cohen et al. 1983; Shipstone et al. 1988; McDermott. Et al., 1992); potential difference is confused with current or energy defined as "strength" of a battery or "force of the current" (Psillos et al. 1988; Duit & von Rhoneck, 1998); potential differences within a circuit depend on its topology (McDermott & Shaffer, 1992); no current implies no potential difference (Cohen R. et al. 1983); parallel resistances decreases circuit resistance (McDermott & Shaffer,1992); resistance considered only as "obstacle" to current (Cohen et al. 1983); difficulties on Ohm relation (Liegeois & Mullet, 2002); local reasoning in analyzing a circuit (Shipstone et al. 1998; Duit & von Rhoneck, 1998); and sequential reasoning in analyzing a circuit (Duit & von Rhoneck, 1998). Moreover, students often fail to understand that potential differences in a circuit depend on its topology (McDermott L. C. & Shaffer P.S 1992); finally, one common idea among students is that across an open switch there cannot be a potential difference because the current is zero (Cohenet et al. 1983). Finally, data in the literature support the fact that students (Duit & von Rhoneck, 1998) as well as teachers (Testa & Michelini, 2006) focus their attention on one point in the circuit and ignore what is happening elsewhere.

Keeping in mind these results, suggested by Physics education research, the project we are carrying out for teachers' training would suggest and test some improved primary education paths, in different specific content areas, to help teachers deal correctly with disciplinary contents, to motivate them in teaching Physics and Science and to probe their difficulties.

Teachers' training is structured along these steps:

- energy as regulator of natural phenomena, as a physical quantity that is conserved, i.e. can be calculated by using a comprehensive set of rules (Feynman et al. 1963 pp4-1 to 4-80) and that can be stored and transferred from a system to another (KPK);
- extensive and intensive quantities: the difference of potential (dop) as the "driving force" for the flux of an extensive quantity (treated as a "substance") in natural processes;
- elementary concepts to study various processes: amount of moving substance, current of substance, difference of potential, resistance and capacitance;
- interpretation, based on the analogy to fluids, of electric processes in terms of the elementary concepts.

2.1 Step 1: Introduction to energy

A theoretical lesson provides the teachers with a shared language to describe the model of energy carriers and exchangers. Such a shared language is applied to simple examples taken from everyday life. Teachers, working in groups (Figure 1) are subsequently invited to explore simple artifacts (hand torches, steam boats, solar vehicles, wind and hot mills, rockets fueled by pumps or chemical reactions, solar moving animals, etc) and interpret them in terms of energy, drawing the relative diagrams of energy flow. To support reasoning and communication, teachers use cards or graphic software based on icons with combination rules coherent with the approach of the course.

Figure 1: Teachers working in group, constructing energy models with cards or software.

As individual homework, teachers analyze complex processes in different scientific contexts (photosynthesis, alimentary chains, water cycle, respiration, digestion, blood circulation etc.) and build the corresponding energy flow diagrams.

2.2 Step 2: Introduction of the elementary models

The elementary models are introduced to teachers in three steps: execution of experiments with a specific aim, discussion of similar experiments and collective workshops.

Teachers are assigned to 3 groups. Each group, organized into two subgroups, performs an experimental subroutine concerning the same elementary concept in two different physical contexts: water and heat (Table 1).

The available equipments allow the experiments to be easily performed (Figure 2).

The experimental activities are guided by handouts to help teachers identifying the “substance”, the independent variable, the dependent one, the parameters, how they can measure the flowing substance, the relation between independent and dependent variables and what happens if the parameters change.

After the experiments, each pair of subgroups meets to compare and discuss the subroutines. This effort is aimed at identifying the elementary concepts of current and potential difference, current and resistance, capacitance and potential difference, and their relationships, keeping the other variables constant as parameters.

Then a plenary section enables the three groups to share their results and considerations, and to identify and discuss the relationships between elementary concepts involving the three variables: Ohm’s law relating current, potential difference and resistance (Figure 3(a)), and the law of capacitance relating potential difference, amount of substance and capacitance (Figure 3(b)). A triangle helps teachers remember and combine the various quantities.

Groups	Group 1	Group 2	Group 3
Elementary concepts	Experiments to introduce the potential difference and its relationship with current	Experiments to introduce resistance and its relationship with current	Experiments to introduce capacitance and its relationship with the potential difference
Experiments in water context	1(a) the amount of water flowing through a hole and a pipe to the bottom of a cylinder as a function of the water level in the cylinder during a certain time period;	2(a) the amount of water flowing as a function of section and length of a pipe connected to a hole to the bottom of a cylinder (maintaining constant the water level) during a certain time period;	3(a) the level reached by the same amount of water poured in cylindrical container of different sections;
Experiments in heat context	1(b) the heat transfer to water placed on a thermostat as a function of the heater temperature during a certain time period.	2(b) the heat transfer to water placed on a thermostat during a time period as a function of the contact area and of the thickness of the layers of refractory stone placed between the container and the heater.	3(b) the temperature reached by water in a container heated for a certain time period as a function of the quantity of water.

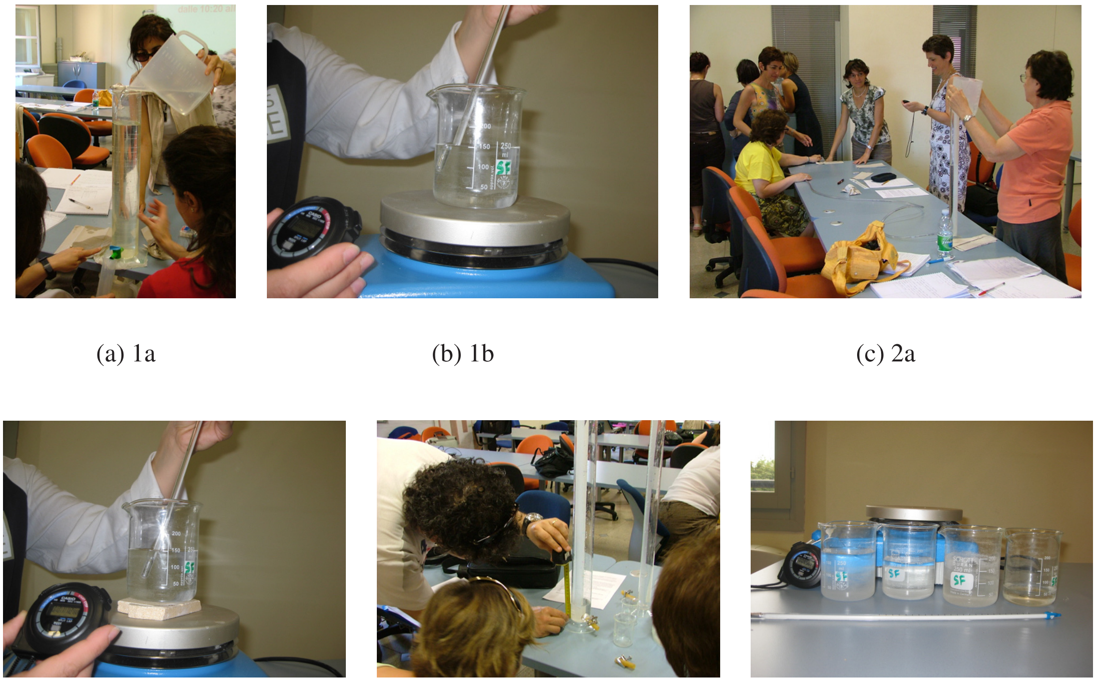
Table 1: Experiments to introduce elementary models.

2.3 Step 3: Application of the elementary models and interpretation of the behaviour of hydraulic circuits

The hydraulic circuits consist of a source (reservoir filled by a pump) with three taps at different heights, fans (flow-meters), vertical pipes open at the top that can be inserted along the circuit (pressure probes), various tube connectors and a basin collector. Working air bubbles out of the circuit is recommended.

The handout, that teachers follow, requires identification of the basic concepts: energy exchangers, current, potential difference, resistance and capacitance in the hydraulic system. Then it proposes 13 experimental situations with questions, including schematic drawings. For each experiment the requirements are:

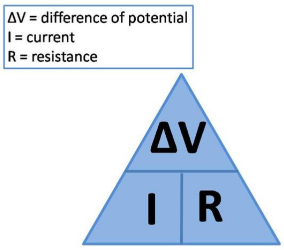
- to identify the parts of the schematic model and mark them with tags: T: energy exchangers; I: Current; V high and V low potential difference, R: Resistance; C: Capacity;
- to write a prediction about the outcome of the experimental situation, supported by graphics;
- to briefly motivate the prediction using the basic concepts;



(a) 1a (b) 1b (c) 2a

(d) 2b (e) 3a (f) 3b

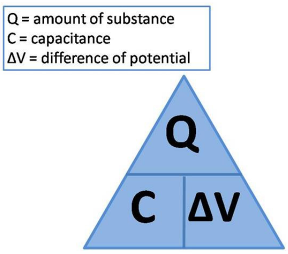
Figure 2: Experimental setups for step 2 activities.



$$\Delta V = IR$$

$$I = \frac{\Delta V}{R}$$

$$R = \frac{\Delta V}{I}$$



$$\Delta V = \frac{Q}{C}$$

$$C = \frac{Q}{\Delta V}$$

$$Q = C\Delta V$$

Figure 3: (Left) Triangle and relationships of the Ohm's law. (Right) Triangle and relationships of the capacitance law.

- to carry out the experiment;
- to mark the predictions that do not fit with the experimental observations using a pen of a different color, noting what consideration it would have taken to make the correct prediction.

The first group of inquiries (1-4) is designed to help teachers recognizing and applying the basic concepts to various elements of the circuit. The second group consists of experiments on circuits with one resistor (5-7), two resistors in series (8-10) and two resistors in parallel (11-13), in configurations of open and closed circuits (Table 2, first and second columns).

2.4 Step 4: Electric circuits and interpretation by analogy of their behaviors

The electric circuits are made by a battery and bulbs linkable in various configurations. A voltmeter is supplied to measure the potential difference. The handout for teachers supplies the scheme of the electric circuit to be considered and, by analogy, the corresponding hydraulic circuit. To promote the use of analogy as a means of explicit reasoning, the questions remain the same as in the hydraulic case. The first question for the electric circuit corresponds to the fifth step of the hydraulic circuit.

Each row of Table 2 shows the drawings of the hydraulic circuit and the analogous electrical one, together with the question referring to the hydraulic circuit only.

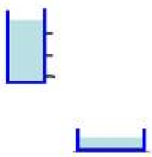
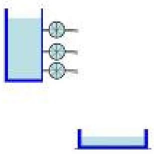
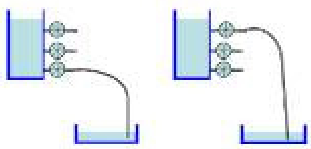
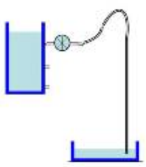
HYDRAULIC CIRCUIT Schematic drawing	**Description of the experiment and question**	**ELECTRIC MODEL Schematic drawing**
	Flow of water from holes at different heights - Fill completely the reservoir making sure that all taps are closed. Open the three taps: how are the jets?	
	Flow of water from holes and fans at different heights - Connect three fans to the three taps. Open the three taps. How do the fans move? Why?	
	Flow of water from holes and fans connected through a tube to the basin collector - Open the taps: how do the fans move? Why?	
	As in the previous case, but now a segment of one of the three tubes is raised over the level of water in the reservoir. How does the fan move? Why?	

Table 2 Continued on Next Page ...

Table 2 – Continued

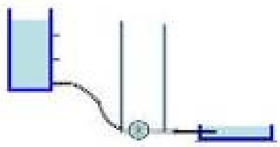
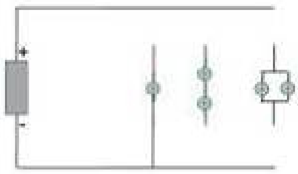
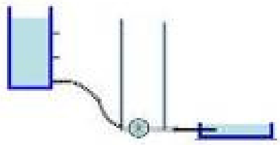
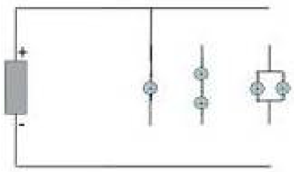
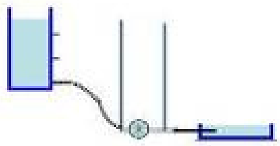
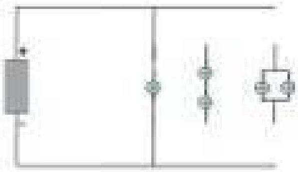
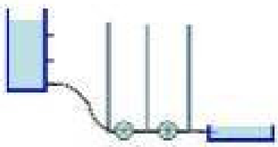
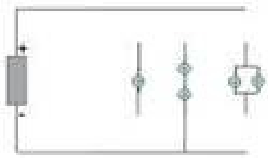
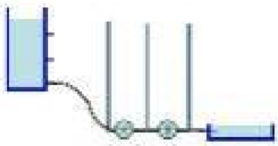
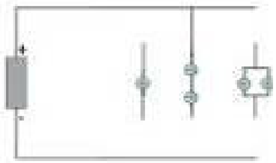
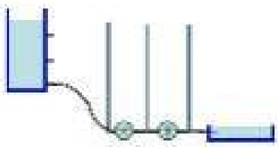
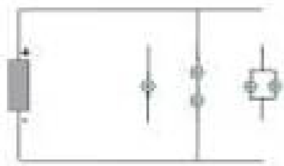
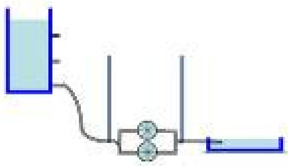
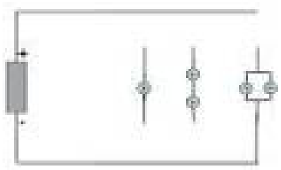
HYDRAULIC CIRCUIT Schematic drawing	**Description of the experiment and inquiry**	**ELECTRIC MODEL Schematic drawing**
	Connect a tube to a tap, then a vertical pipe, a fan, another vertical pipe and a tube connected to the basin collector through a tap. Close the tap of the reservoir and open the tap of the basin collector. What will happen? Why?	
	As in the previous configuration: open the reservoir tap and close the basin collector tap. What will happen? Why?	
	As in the previous configuration: open both taps. What will happen? What is the function of the vertical pipe? Why?	
	Insert another fan and another vertical pipe in series with the previous circuit. Close the tap of the reservoir and open the tap of the basin collector. What will happen? Why?	
	As in the previous configuration: open the tap of the reservoir and close the tap of the basin collector. What will happen? Why?	
	As in the previous configuration: open both taps. What will happen? Why?	
	Connect a tube to a tap of the reservoir, then a vertical pipe, two fans connected in parallel, another vertical pipe and a tube connected to the basin collector through a tap. Close the tap of the reservoir and open the tap of the basin collector. What will happen? Why?	

Table 2 Continued on Next Page . . .

Table 2 – Continued

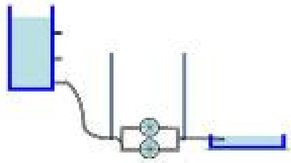
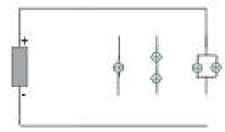
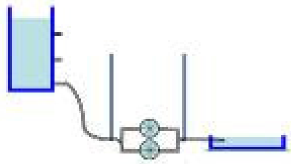
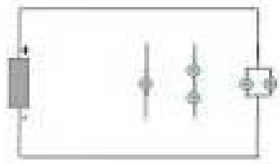
HYDRAULIC CIRCUIT Schematic drawing	Description of the experiment and inquiry	ELECTRIC MODEL Schematic drawing
	As in the previous configuration: open the tap of the reservoir and close the tap of the basin collector. What will happen? Why?	
	As in the previous configuration: open both taps. What will happen? Why?	

Table 2: Questions referring to the hydraulic circuit only, and drawings of the hydraulic and the analogous electrical circuit.

Teachers' predictions, made before the experiments and the reasoning they claim to support them, will be analyzed in the next section to investigate the role and the kind of models used to interpret the circuit behaviors.

3. Results of the in-service teachers' training on hydraulic and electrical circuits

The results presented here are from about 90 in-service teachers (having different ages, years of service, curricula) belonging to 15 different schools in three different cities: Modena, Reggio nell'Emilia and Parma.

The first 4 questions have allowed teachers to begin focusing on the elementary concepts of drop, current and resistance in the hydraulic context. For the first question, designed to introduce dop and current, teachers presented 81% correct predictions (9 groups out of 11). Only two groups with wrong estimates, make a wrong prediction for the second question too (2/11 = 18%).

Data analysis of the first question shows the following wrong prediction for the drop that however allow teachers to make correct predictions on the water jets: drop as due to

- the height of the reservoir (2/9 = 22%);
- the difference in level between taps (2/9 = 22%);
- the difference in level between the water level in the reservoir and in the basin collector (3/9 = 33%);

- the difference in level between each tap and the water in the basin collector (2/9 = 22%).

In only two cases did participants make wrong predictions on the water jets. Teachers say respectively that they will observe "the same jets because the pressure is equal at all points" and that "increased flow (is) what comes out of the higher tap because the water pressure is greater".

The second experiment, which differs from the first by an additional fan, aims at introducing the concept of resistance. In this case, teachers suppose that the flow is slowed down (9/11 = 81%).

The two groups (2/11 =18%) that make a wrong prediction are the same that had not recognized the existence of pressure drop. The group (1/11 = 9%) who stated that "the pressure is equal in all points" draw the jets still in a similar manner to the test 1 (the jet leaving the higher tap goes further) even though their justification is correct: "the pressure is greater at the bottom of the reservoir". The other group now correctly draws the jets, but predicts that the fastest fan is placed on the highest tap. In this inquiry, the teachers reflect on the role of the fan, recognized as resistance and at the same time as an indicator of current: the higher the current, the greater the angular velocity of the blades of the fan (10/11 = 90%).

The third and fourth questions are proposed to reinforce the concepts previously introduced through situations inducing cognitive conflict. In the third experimental situation 7 groups out of 11 (64%) say that the tube, representing a resistance, slows the flow, 2 groups of 11 (18%) say that it is irrelevant because the tubes are of the same section as the hole on the reservoir (1/11 = 9%) or because "the tube is inserted after the fan, so that it does not change the fan speed in relation to previous experiments", (1/11 = 9%); 2 groups (2/11 = 18%) say that the fan with the tube runs faster, but does not give any explanation.

In the fourth situation, the group predictions indicate that 6 groups (6/11 = 54%) focus only on one part of the tube: the upward section (4/11 = 36%) that leads them to conclude (4/11= 36%) that "lifting the tube, the fan slows down, due to the greater slope" or the downward section (2/1 = 18%) that leads them to hypothesize that the fan runs faster, compared to the previous situation, because more drop is now created.

The analysis of 58 forms from 5 to 13 on the hydraulic model provided by 11 groups, shows that in almost all cases the predictions are phenomenological descriptions because teachers consider the water level in the tubes (54/58 = 93%), the movement of the fan (21/58 = 36%) and water circulation or lack thereof in the tubes (15/58 = 26%).

In the 5th and 6th questions, which refer to open circuits with a single fan and a closed tap, the model of communicating vessels (32%) has prompted the teacher to estimate the water levels achieved in the vertical pipes before and after the fan. Continuing with enquiries, teachers no longer mention this model and try thinking in terms of constant potential or zero drop.

The concept of potential and potential difference has been recorded in 67% (39/58) of cases of open and close circuits and in 89% of them (35/39) it is cited in the explanations. The current is quoted in 22/58 = 38% of cases overall, considering both predictions and explanations and by a small minority (2/22 = 9%) it is considered to be the only motivation. A deeper analysis of the teachers' responses mentioning the drop as cause of flux, shows that the drop is cited as the only justification in 41% of cases (16/39), while in 15% of cases (6/39) it is cited as a cause of current too, and in 28% of cases (11/39) it is cited along with the current. Anyway the current is never considered the cause of pressure drops.

In closed circuits, the fan resistance is identified together with the drop as the variable that determines the current (10/33 = 30%), while in very few cases (2/33 = 6%) an estimate of the speed of rotation of the fan is made to indicate the intensity of the current.

In the hydraulic circuit with two fans in series and in parallel, the teachers discuss neither the fan speed, nor the total resistance of the circuit. In almost all of these situations they do not write predictions but prefer to present them only verbally. In any case, they constrain themselves to consider only the water level in the vertical pipes or to assume that the two fans are running at the same speed, without adding any comparison between circuits with a single resistor, in series or in parallel.

In the following we report the few cases of wrong predictions. They are related to experiments 7 and 13. In experiment 7, related to a closed circuit, a group makes the prediction that the water rises to the same height in the vertical pipes, although it is recognized that the fan turns to the passage of current.

The two failed predictions, related to the parallel circuit (question 13), consider twice the overall effect of the resistance compared to circuit with a single fan.

The analysis of teachers' works on the electric model is made based on 81 answers to questions 5 to 13, provided by 9 groups.

Teachers' predictions are focused on bulbs' light turned on or off (59/81 = 73%), on potential difference along the circuit (50/81 = 63%) and on current (21/81 = 26%).

A peculiar result of the electrical circuit is the presence of the drop only as prediction (50/77 = 65%), while current as motivation (37/58 = 64%). 50% of this 64% include explicitly current as cause of drop. However, this situation needs to be further investigated because in many cases teachers do not show a correct use of implication symbols or of logical connectives.

In closed circuits, the electrical resistance of the bulbs and their brightness are cited in 16/27 = 59% and 14/27 = 52% of cases respectively. In 66% of predictions for bulbs in series, teachers recognize that the overall resistance of the circuit increases. Only 33% of the groups consider resistance properly in the case of bulbs in parallel. Both in the circuit in series and in parallel there is an incorrect prediction of 2/9 = 22%.

Finally, we report some teachers' mistakes. The group that misses the 5th question predicts the voltage of the battery at all points of the circuit. In the series closed circuit, 2 groups (2/10 = 20%) state that the bulb closer to the positive pole is brighter than the other. In the closed parallel circuit 2 groups (2/10 = 20%) say that the circuit resistance increases.

4. Discussion and conclusive remarks

All the considerations to interpret the results are related to sequencing the hydraulic circuit, followed by the electrical circuit. As a consequence, at the moment, we are unable to definitively distinguish what is determined by the specific context from what is due to the sequence.

In the following we discuss the results of the two investigated contexts and draw some general remarks.

In almost all hydraulic experimental situations, teachers' estimates are focused on phenomenological descriptions. The first experimental situation identifies 4 naive ideas of pressure drop, but since all of them imply a suggestion of gradient, they have allowed teachers to make accurate representations of water jets. Our results suggest that teachers' inclination is to consider each circuit element in a reductionist way (Testa & Michelini 2006). For example, in question 3 the tube is considered only as a resistance, forgetting that having one entrance and one exit can vary the drop depending on the difference in height it creates; in the 4th experiment the upward part of the tube is thought separated from the downward one; the fan is only considered as a barrier to current and not also as an opportunity to move, especially in the test with parallel fans.

However the hydraulic model has created the opportunity for trainers to learn properly the concept of pressure drop as the cause of currents both for open circuits (communicating vessels) and for closed circuits. Moreover the fans are correctly recognized as resistors which cause a fall in potential and a decrease of current.

In regard to the analogous electric circuit, we can draw the following conclusions: the teachers make use of potential drop, but differently from the hydraulic case. Indeed the mention of potential drop, not only in reasoning but also in prediction, suggests that teachers consider potential drop as a phenomenological aspect of electrical circuits just as bulbs lightening and their brightness. This result could be due to the fact that in electrical circuits potential drop is the result of a measurement.

Anyway teachers analyze properly the open circuits and they are well oriented to provide the correct behavior of closed circuits, even with numerical indications of potential drop along the circuit, before and after the bulbs, with the exception of the parallel circuits.

For an understanding of parallel circuits it seems to be necessary to overcome the reductive model of resistance as a barrier to current and to consider it rather as an opportunity for current transport.

In conclusion, experiments on the basic elementary models (1-3) and the first 4 questions on hydraulic circuits have allowed teachers to focus on the concepts of potential drop, current and resistance, even if the analysis of results suggests that the last two are adequately understood only if confined to the hydraulic model, but not so sufficiently consolidated to be always correctly transferred to the electrical situation. This suggests the inclusion of further training path specific situations to create conceptual conflict for resistance and current in hydraulic context in a way similar to what we did with questions 3 and 4 concerning the concept of potential drop.

When teachers already have an interpretative model previously established, they are able to orientate themselves, whereas when the model is absent or only mathematically introduced, they are not able to transfer it to others contexts. Elementary consolidated patterns of interpretation (communicating vessels, potential drop as the cause of current) enable teachers to make predictions and to interpret correctly the behavior of the majority of hydraulic and electric circuits, despite their differences and peculiarities.

The electrical circuit is certainly far away from the sensitivity and the propensity of primary school teachers, but the opportunity to analyze it in analogy to what is done in the hydraulic circuit has enabled them to address it. Teachers have in fact benefited from models borrowed from hydraulic circuits and, by analogy, have made in most cases successful predictions on electrical circuits.

Finally, the analysis, of which and how many variables are considered, underlines the difficulties of teachers to consider three variables at the same time. We believe that further situations of conceptual conflict where teachers are obliged to consider three variables simultaneously will help them to build a mental model for Ohm's law and the concept of resistance.

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