Using students’ learning to improve teaching: the case of the cream rising to the top

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Abstract. Teachers go to class to teach their students. One may question how often teachers use students’ visualisation of a concept to probe students’ understanding and to improve their own teaching. This paper focuses on the link between analogical reasoning and mental modelling in the teaching of electric circuits. A study conducted with 17-year-old physics students of different ability is described. From the results of a pre-test, post-test and semi-structured interviews using an ‘analogy prompt’, it will be shown how, when learning is meaningful, analogy generation can be developed and modified easily by students to relate the analogue to the target in question, thus providing evidence of the existence of scientific models of concepts in the minds of the students. It will be argued that the teaching of abstract concepts may be improved by using analogies indicated by high ability/gifted students who manage to develop a scientific view of concepts in question.

1. Introduction
Teachers go to class to teach their students using different pedagogies. One may question, however, how often teachers use students’ visualisation of a concept to probe their students’ understanding and to improve their own teaching methods. This paper gives a brief overview of the literature related to mental modelling and analogical reasoning, describing how mental models and analogies are related. A research study conducted with physics students at pre-university level of different ability is described with the aim of establishing students’ understanding through the course of study. The students answered questions related to electric circuits, through tests and interviews with the researcher. It was important to try to probe how students of different ability reason as their understanding of abstract concepts was developing. To help students’ visualisations of concepts related to the topic in question, students were introduced to analogies by using a PowerPoint presentation. During the interviews, students were asked to describe how the circuits, represented on given circuit diagrams, work in terms of a water analogy prompted by the researcher. Parts of some interview transcripts are presented to show the variation between students’ responses. Analysis of the results not only helped to clarify ideas related to the aims of the research but also went further in helping the author to recognise that links exist between high academic ability and effective analogical reasoning.
2. Background

2.1. About Mental Models
Mental models are psychological representations of real, hypothetical, or imaginary situations [1]. Such models thus refer to personal knowledge that each of us builds as we perceive the world [2,3]. Mental models are considered as intermediate steps we create as our ideas move towards scientific ones. Some authors have emphasised that models and modelling are central to understanding key concepts in science [2, 4–6]. Many researchers are of the opinion that to understand science is to understand the models used by scientists.

2.2. About Analogies
Analogies are closely related to mental models. Using analogies means linking/mapping/comparing elements of the analogue to those of the target, for better understanding. This author agrees with Duit et al [2] and Clement [7] in seeing analogy as a tool which can help in mental model development and evolution, as a concept is being understood. When using analogies, it is important to try to select an analog that shares as many similar features with the target concept as possible. A number of researchers have also looked into spontaneous analogy generation by students and how this may be used as a tool to construct and refine ideas during learning [4,7–10]

Most of us have a natural tendency to be attracted by similarities. We tend to look with some surprise, for example, at identical twins and take photos to remind us of an almost perfect reflection of a river bank on a perfectly smooth water surface. We are likewise easily drawn to explain in terms of similarity.

As Glynn [11] rightly puts it: ‘Teachers often use analogies and are unaware of it—they are using them automatically. Whenever they begin an explanation with “It’s just like…,” “It’s similar to…,” or “Think of it this way…,” they are using an analogy to explain a concept to their students.’ Personally, I believe in the power of analogy since it helps those using it to associate one thing with another. Such an exercise provokes thinking which helps prediction, analysis, further refinement of thought and its development. It may perhaps also help memory retention.

2.3. Linking Mental Models to Analogy
The relation between mental models and analogies has been presented diagrammatically by Duit [12] (see Figure 1). An individual may already have a mental model of the analog. As one compares elements of the analog to those of the target (this is the analogy) a mental model of the target may evolve, helping ideas to become more clear. This leads to understanding.

3. The study

3.1. Aims of the study
This study was being conducted with the following aims:

- To learn about students’ alternative ideas related to electric circuits;
- To search for evidence on whether students’ understanding could be helped by using specific practices that help reduce these alternative ideas, allowing for meaningful learning to happen.

3.2. Methods and sample
The sample for this research study consisted of 49 physics students, who were 17 years of age and who were in their second year of study at a pre-university college in Malta, covering an Electric Circuits course with me. It was explained to students that participating in this research study would help them also in gaining more insight into problems they might have with understanding circuits. All students voluntarily agreed to participate in the research study. Students sat for a pre-test and a post-test consisting of questions probing understanding of electric circuit concepts. At the pre-test stage, students also sat for a Test On Logical Thinking (TOLT) [13]. Performance on TOLT helped to categorise the students as low, average and high ability.
Figure 1. Linking analogy to mental model [12].

Midway through the course a PowerPoint presentation including analogies related to the electric circuit concepts - current, resistance and potential difference - was shown to students. It was thought that showing this to students at this time, would allow students to reflect on what they had seen, with the hope of improving their mental models of the topic by the end of the course. The aim of this presentation was to help the students to link concepts related to current electricity to other concepts used in other physics topics, through the use of analogies. Class discussion was encouraged allowing students to become metacognitively aware of their doubts and try to solve them. Two slides from this presentation are shown in Figure 2. These are linked to ideas presented later in the discussion of the results. After course completion, one-to-one semi-structured interviews with 9 students of different ability were conducted during students’ free lessons, to probe by how far students’ understanding had developed.

3.3. Circuit diagrams used and questions asked in the interviews

The following simple circuit diagrams were shown to students, the understanding of each being probed one after the other. Ammeters and voltmeters were purposely not included in these diagrams and equal resistances only were considered. This was done to present simple ideas, avoiding distractors, as much as possible (see figure 3).

Figure 2. Two of the analogies used in the PowerPoint presentation.
Figure 3. The circuit diagrams used during the interviews.

Students were shown Figure 3(i) and asked for their mental picture of what goes on in the circuit when the switch is ON. Students were asked to compare how the circuit works with something that helps them understand better. Students were then shown Figure 3(ii) with 2 equal resistances connected in series and they were asked to say what happens, now that changes were made to the circuit. Showing students the third diagram in Figure 3(iii) led to the most important part of the interview when students were asked to say how the circuit works when the resistances are connected in parallel. The aim of the interview was that of motivating students to talk about their visualisations of how circuits work when resistors are connected in different ways. My underlying hypothesis has always been that if students could talk about their visualisations and compare their ideas of what is happening in a circuit to something else, then their learning would be meaningful and they would give better qualitative explanations. So, at this point, whether or not students had come up with some comparison or not, I decided to make an ‘analogy prompt’ to students, as follows:

‘Let us say that with $S_1$ only closed, 100 cm$^3$/s of water was flowing through the circuit. What do YOU imagine happens when $S_2$ is switched on?’

Students were asked to think in terms of the water analogy because this analogy is quite commonly used with reference to electric circuits and also because it had been referred to in the PowerPoint presentation through the course.

3.4. Results

The results of the pre-test and the post-test had shown that students find significant problems when they deal with parallel circuits. Some students found difficulty to realise and explain how resistance is reduced when resistors are connected in parallel. It is the number of resistors some students focus on and not how they are connected. Furthermore, some students had difficulty understanding that the potential difference across parallel resistances is the same when resistors are connected in parallel, especially when the resistances are unequal.

The interviews probing students’ understanding once again indicated that students could talk about the simple circuit and how it works, even if they could not necessarily compare the system to anything else. Students could also talk about the series circuit, recognising the increase in resistance and the decrease in current within the circuit. On the other hand, students faced problems when they came to explain the parallel circuit and how this works. The problems were also related to potential difference across resistors connected in parallel.

When prompted to discuss the parallel circuit in terms of the water analogy, 7 out of 9 students explained to me that they saw the original current in the circuit with one resistor, dividing into two halves, each half passing through each resistor when the second resistance is added in a parallel branch.
Working with the analogy proposed to them, they saw the same thing with the water circuit. The following is the answer from one student:

‘In the water circuit, 100 cm$^3$/s divides into two. 50 cm$^3$/s pass through each path/pipe. The battery is the pump, pushing the same amount of water in any circuit.’

The answers from the other 6 students were similar. Students divided the 100 cm$^3$/s into two. In other words, these students had the same alternative idea whether it was an electric circuit or a water circuit, thinking that the battery/pump alone controls the flow of charge/water in the circuit.

Other student’s answers, apart from the 7 already mentioned, were as follows:

Electric circuit:  ‘The potential difference across the resistors connected in parallel stays the same as that of the battery.’

Water circuit: ‘Here I cannot say. I am not sure and I am mixed up. I see the battery as a motor which keeps supplying the 100 cm$^3$/s of water.’

It seemed that this student could not link the ideas on electric circuits retained from rote learning to the ones that could be offered relating to the analogy.

Only one student, Dan, out of the 9 interviewed, recognised the extra path available for current in the parallel circuit. Dan was a high ability student who immediately saw a lower resistance resulting in a bigger current within the parallel circuit. Dan talked about the water analogy without even being prompted to do so. The following is an excerpt of Dan’s interview, where ‘I’ represents the Interviewer and ‘D’ represents Dan:

D: ‘You can consider the battery as a tank which is placed high up so that you can create the potential difference. You put the tank high up and a pipe lower down. In this case you are using 2 pipes since there are 2 resistances in parallel. The 2 pipes are in parallel. The water comes out of the tank more quickly from 2 pipes instead of 1. More water comes out, because if there is just 1 pipe, a certain amount of water is released, but if you open another outlet there will be two pipes. The pipes have to be the same width if the resistances are the same and more water comes out.’

And later in the interview:

I: And if you were to imagine a certain amount of water flowing, say 100 cm$^3$/s flowing when you only had one resistor?

D: This is the current in terms of water flow. Now with electrons the current is electrons flowing per second. In fact, current is charge transfer per unit time.

I: So now, how would you imagine the situation when switch 2 is switched on?

D: Now the rate will be increased. It will be doubled. Double what it was before, since a new path has been introduced. They both have the same pressure, these pipes, since the voltage remains the same. The two pipes will have the same pressure of water through them, because the pressure is the same and you’ve opened a larger flow of water. So now you have an extra 100 cm$^3$/s. Now you have 200 cm$^3$/s.

Dan’s interview was coined ‘the case of the cream rising to the top’. Dan was the only high ability/gifted student amongst the 9 interviewed students. He showed that he mentally visualised the electric circuit, its function and the meaning of potential difference. By being able to use the water analogy in a way which made sense to him in his descriptions, he gave proof of meaningful learning.
4. Discussion

It must be emphasised that the ease, clarity and conviction with which Dan explained his views analogically and scientifically was striking. The interchange of ideas from analogue to target, and vice versa, showed deep understanding. Dan focussed primarily on the issue of having a tank and connected pipes to it, allowing water to flow. His attention was not focussed on a pump. Indeed, a pump was never mentioned in his description. The flow was explained in terms of the gravitational field concept. Dan linked water height to pressure and imagined potential and potential difference as some kind of electrical pressure. On the contrary, even if some of the other students referred to gravitational potential, all of them focussed on the pump as the battery. In both analog and target, for them, the pump/battery allowed for a fixed supply of water/current. Nothing else mattered.

With regard to the presentation using analogies mid-way through the course, it seems that this had not worked as well as I would have imagined. Perhaps periodic reinforcement of ideas related to the analogies would have helped students more. Of course, it may also be that intrinsic motivation on the part of the students to think and relate the ideas from the analogies to the work covered on circuits to help build their scientific model of concepts involved, was lacking. Even so, it must be admitted that if the use of analogies works with a few students, analogies can help to improve learning, under the condition that the analogy used is chosen carefully making sure it best fits the purpose. One must remember, however, that the same alternative ideas may exist with both targets and analogs. Schwedes et al [14] claim that similar alternative ideas exist when using the water analogy, as in electricity. Students assume that the same battery/pump supplies the same current. This was indeed evidenced in this research and teaching must address this problem with the use of analogy to help make teaching more effective. Moreover, allowing students to talk about analogies spontaneously can help in probing understanding and in exposing what mental models students seem to hold of a concept. Furthermore, in dealing with parallel circuits using the water analogy, it seems better to concentrate on a tank as a reservoir with connected pipes, rather than putting all the focus on a pump in the water circuit. Overall, this study provides more insight as to how teaching of abstract topics may be improved. Meaningful learning can happen through the use of analogies. Highly able/gifted students think, re-think and refine their ideas and also reason analogically in a way that effectively aids their understanding of abstract concepts. High ability/gifted students have the potential of knowing what helps them understand. Their explanations offer causal reasoning. The academically highly able/gifted students have a strong academic identity which, when acknowledged and used carefully by teachers, may provide a way that helps teaching become more effective. Probing and using the analogies as indicated by high ability learners can help to improve the teaching-learning process. This study helps to add to the literature on the gifted by highlighting a link between the highly able/gifted and effective analogical reasoning. This link may not have yet been emphasised enough in the literature related to the gifted. Gross claims that in 1981 Robert Sternberg ‘noted significant differences between gifted and non-gifted learners in tasks involving analogical thinking’ [17]. The present study gives empirical evidence of this.

5. Conclusion

This research study emphasises how students completed a course of study in electric circuits and some were still not visualising how an electric circuit works. Problems were more significant in the area of parallel circuits. Visualisation to understand concepts in electricity can be improved with the systematic use of analogies during teaching.

This study has moreover highlighted the link between high ability/gifted students and effective analogical reasoning that makes learning meaningful. This link does not seem to have been emphasised enough, in earlier published work related to the gifted. In spite of this, it must be acknowledged that this link presents a very important issue for education. It can indeed present a step forward in the right direction in helping teachers become more effective in their job. Through further research in the classroom, teachers can probe and discover what analogies their high ability/gifted students use to develop their scientific views of the various concepts, especially abstract ones, in different topics. Teachers can then use these analogies in their teaching for the benefit of all students.
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