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Students Reinventing the General Law of Energy Conservation

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Summary

Problem definition

In traditional education students have trouble in applying the concept of energy conservation to various situations (Borsboom et al., 2008; Liu et al., 2002) and in revising it when necessary (Kaper, 1997). The general law of energy conservation is mostly taught as an unsubstantiated fact. This may be a reason that students do not acknowledge the general applicability of the law and do not revise their life-world conception of energy (Borsboom et al., 2008; De Vos, Bulte, & Pilot, 2002; Doménech et al., 2007; Driver & Warrington, 1985; Kaper, 1997; Liu et al., 2002).

To let students substantiate the general law of energy conservation with evidence we have chosen to use guided reinvention (Freudenthal, 1991) as our conceptual approach. Freudenthal states that knowledge and ability, when acquired by one's own activity, stick better and are more readily available than when imposed by others.

In a context-based approach concepts gain meaning for students by involving them in scientific or socially relevant activities (Bulte et al., 2006; Gilbert, 2006). To make the students appreciate the relevance and usefulness of science in general, innovation committees for the exact sciences in the Netherlands have advised a context-based approach (Boersma et al., 2007; Commissie Vernieuwing Natuurkunde onderwijs havo/vwo, 2006; Driessen & Meinema, 2003).

Two important problems to solve in context-based education are the difficulty to achieve transfer from one context to another (Parchmann et al., 2006; Schwartz, 2006; Goedhart et al., 2001) and the difficulty to develop abstract concepts in contexts (Parchmann et al., 2006; Pilot & Bulte, 2006; Schwartz, 2006). Both difficulties concern the versatility of students' resulting conceptions. The problem of lack of transfer concerns the applicability of students' conceptions and the problem of lack of developing abstract concepts concerns the revisability of students' conceptions.

To contribute to a solution to these two difficulties and to let students substantiate the general law of energy conservation with evidence we have chosen to combine a guided reinvention approach with a context-based approach.

Guided reinvention does not mean that the students are following the historical invention of the general law of energy conservation: in hindsight we can guide them along a more efficient route. Historically the energy concept has grown from the invention of various partial laws of energy conservation (e.g. Huygens' discovery of the conservation of vis viva for elastic collisions (Hugenii, 1728)), and connect those when a new situation calls for it. Joule described many of such partial laws of energy conservation connecting caloric, vis viva, and other variables. Because of knowing about all these partial laws he was already convinced there would be a fixed relation between mechanical energy and heat before he performed his famous experiment (Joule, 1850). We have chosen to try bringing our students to a similar conviction as Joule, by letting them reinvent several partial laws of energy conservation concerning gravitational, thermal, and kinetic energy (conceptual learning step I). Subsequently we guide the students in combining those partial laws of energy conservation into one combined law to expand the applicability of the laws (conceptual learning step II). The possibility of combining partial laws whenever a new situation calls for it may suggest to students, like it did to Joule, that conservation of energy is applicable to any situation (conceptual learning step III). We expect that in such a learning process the applicability and revisability of students' conceptions of energy will grow.

Gilbert (2006) chooses 'context as the social circumstances' as the most promising category of contexts. Boersma (2007) specifies this choice more precisely by choosing authentic practices as contexts for education. A way to show the relevance of what is learned is the problem posing teaching approach. Lijnse and Klaassen (2004) state about this approach that learning should be driven by problems that students can identify with. To motivate students through the learning process several researchers combine the use of authentic practices with the problem posing approach (Dierdorp et al., 2011; Westra, 2008; Bulte et al., 2006). We have chosen to adhere to such a combination as well.

For this research project we have investigated the interaction of concept and context in a teaching-learning sequence that aims at a versatile conception of energy, leading to the main question:

How do context and concept interact in context-based education that is suitable to develop a versatile concept of energy?

Method & Analysis

By using the method of design research (Van den Akker et al., 2006) we have developed a teaching-learning sequence that takes on the challenge of students reinventing the abstract concept of energy conservation in authentic practices. The teaching-learning sequence has been tested during three cycles in fourteen classes of sixteen- and seventeen-year-olds from nine teachers.

We have chosen to use three technological design assignments each intended to guide students to reinvent a partial law of energy conservation: designing lifting apparatus to lift a heavy capstone in ancient Greece (aimed at reinventing $\sum mgh = k_1$), designing a thermostatic water tap (aimed at reinventing $\sum mcT = k_2$), and designing an uphill rollercoaster (aimed at reinventing $\sum mgh + \sum \frac{1}{2}mv^2 = k_3$).

These assignments are followed by two scientific assignments in which students are to investigate the possibilities of describing the earlier technological design assignments with one combined law. The first of these two assignments involves Joule's famous experiment and is intended to combine the first two partial laws

into one: $\sum mgh + \sum mcT = k_4$. The second scientific assignment is intended to also incorporate the third partial law into the combined law: $\sum mgh + \sum mcT + \sum \frac{1}{2} mv^2 = k_5$.
A third and final scientific assignment asks the students whether this combination process is always possible. It is used to test whether students see the need for a further expansion of the law and whether they are capable of reinventing a new partial law ($\sum \frac{1}{2} CU^2 + \sum mcT = k_6$)[1] and combine that new law into the already established one which should result in $\sum \frac{1}{2} CU^2 + \sum mgh + \sum mcT + \sum \frac{1}{2} mv^2 = k_7$. From an analysis of their answers to the final assignment we are able to determine whether the students are convinced that an expansion of the conservation law is always possible.

In developing an educational design three stages may be distinguished: a first try-out to see whether students are able, in principle, to achieve the learning goal, a second try-out to analyze how the steps towards that learning goal function and how they may be optimized, and a final try-out to analyze the conceptual results of the educational design (Plomp, 2007; Gravemeijer & Cobb, 2006; Nieveen, 1999).
The success of each conceptual learning step in our teaching-learning sequence depends on the results of the earlier conceptual learning steps. Investigating whether it is possible for students to follow our trajectory is therefore done one step at a time. Because of this the conceptual learning steps in our teaching-learning strategy are all at a different level of try-out.
The first step of deriving partial laws from measurements has been tried out three times. The second step of combining partial laws has been tried out twice. The third step of extrapolating the combination procedure to make a prediction on whether an expansion of the conservation law is always possible has only been tried out once.

From audio recordings and students' worksheets from the three try-outs we have identified the following four characteristics of authentic practices that contribute to the intended learning process. The problem given to the students in an authentic practice needs to be set in a time or place in which a ready-made solution is not available to make students see the need for performing an experiment. Secondly, the problem needs a solution that cannot be tested on a realistic scale but can be tested only on laboratory scale to make students see the need for a physical law to extrapolate the results of the laboratory-scale test to the real solution. To prepare students for combining partial laws of energy conservation the problem should be such that any solution to it requires an insulated system. Finally, the practice needs to lead in a natural way to a scientific debate on the validity of the law of energy conservation to make

[1] Where U is electrical potential difference across a capacitor and C is the electrical capacity.

students see the need of discussing procedural steps before supporting a generalization of the validity of the law of energy conservation.

The final educational design has been tested on its conceptual results in four classes of sixteen- and seventeen-year-olds from four teachers. It replaced the traditional quantitative introduction to energy in physics. The way in which the students developed the concept of energy conservation was analyzed by observing whether students *revised* their conception successfully and whether they *applied* their conception successfully to various situations.
Students' conceptual *revisions* were traced by analyzing students' worksheets and reports handed in by them during the learning process. Whether the students were able to *apply* their conception to various situations was observed from students' results on quantitative test questions given during a final test. In addition the students were given the Energy Concept Inventory (Swackhamer & Hestenes, 2005) to be able to compare their conceptual results with results from earlier research.
To analyze *revisability* three levels have been defined based on the three conceptual learning steps the students have to take:
Level 1.1: students are able to generalize a partial law from specific situations.
Level 1.2: students are able to combine various partial laws into one combined law.
Level 1.3: students are able to extrapolate the combination procedure for partial laws of energy conservation to establish the general law of energy conservation.
The first two of the three levels we propose could be generalizable to other cases where partial laws occur[2].
To analyze applicability we analyzed students' final reports on whether students applied their reinvented partial law to the given problem (very near transfer). The *applicability* of students' conceptions of energy conservation was further analyzed by students' answers to test questions concerning new situations from the domains investigated in the three technological design assignments (near transfer), and students' answers to a test question concerning a situation from an uninvestigated domain part involving all three terms of the resulting combined law ($\sum mgh + \sum mcT + \sum \frac{1}{2} mv^2 = k_5$)(far transfer).

Results

The results for students applying their conception of energy conservation correctly to qualitative problem situations from the Energy Concept Inventory showed comparable results (a score of 40.9%) to the results for eighteen-year-olds just before their exams (Borsboom et al., 2008). A large percentage of the students (61.8%) realized that applying the reinvented partial law of energy conservation would improve their corresponding advice in the technological

[2] Like the laws of Boyle, Gay-Lussac and Avogadro being three partial versions of the ideal gas law.

design assignments. On near transfer questions comparable to Dutch exam questions on average 71.1% of the students gave a conceptually correct answer. On the far transfer question concerning gravitational, thermal, and kinetic energy 26.3% of the students gave a conceptually correct answer.
By reinventing a partial law from measurements 64.7% of the students showed that they attained revisability level 1.1. 32.4% of the students were capable of combining partial laws of energy conservation correctly and thereby showed that they attained the accompanying revisability level 1.2. Extrapolating the combination procedure to form an opinion about the general validity of the law of energy conservation was only tried out once. None of the students showed a complete discussion of the combination procedure but 38.2% discussed at least one of the procedural steps to substantiate their opinion on the validity of the law. Almost two thirds of all the students concluded that it is always possible to expand the conservation law when necessary and thus that it is generally valid. None of the students stated that expanding the law would not be possible.

The fact that about two thirds of the students attain revisability level 1.1, about one third attain level 1.2, and again about a third take steps towards level 1.3 shows that the corresponding conceptual learning steps I, II, and III are feasible even for sixteen-year-olds. The applicability results have been shown to be comparable to the results for Dutch exam students in traditional education.
In the learning process students showed improvement in skills such as formulating uncertainties for their preliminary design, describing suitable experiments to test their design, performing measurements, deriving physical laws from data, seeing the need for using physical laws to improve designs, and reflecting on the procedure of deriving such laws. In traditional teaching of the subject these skills normally are not addressed. A fruitful combination of reinventing a concept and the use of authentic practices seems possible even for an abstract concept such as energy conservation.
The teaching-learning sequence does take about 30% more time than the traditional quantitative introduction to energy conservation but in our approach an introduction to technological design and the scientific method is embedded.
Of the three conceptual learning steps the last two have been tried out limitedly. The main issues left on these two learning steps are that students had difficulty in applying preconditions (like: insulated system) to their proposed experiments and in recollecting and critically understanding the procedural steps to combine partial laws of energy conservation.
The role of preconditions in the teaching-learning sequence needs to be expanded and recommendations on this have been given. A scientific debate may be added at the end of the teaching-learning sequence after the students have formed their own opinion on the general validity of the law of energy conservation.

In this research the theory on versatility of a concept (Van Parreren, 1974; Dekker, 1993) has been expanded by subdividing it into applicability and various

levels of revisability. An innovative phenomenological approach to teaching the concept of energy conservation that combines guided reinvention with the use of authentic practices has been developed. This offers a way to develop abstract concepts in authentic practices. Characteristics of authentic practices in which such concepts can be developed have been given. By testing this approach a proof of principle has been given that it is possible for students to develop a versatile conception of energy within such an approach.