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A Guided Re-invention Path Towards a More Versatile Concept of Energy Conservation For Secondary School Students

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Abstract

Traditionally the concept of energy conservation is introduced as an undisputable physical law that helps us describe many processes. However the usefulness and the validity of the concept of energy conservation evades many students. We intend to make the concept more useful and less abstract to students. To that end we have them reinvent special cases of energy conservation from practical contextual problems. Thereafter the students are asked to combine those special cases to increase their applicability. By extrapolation of the combination process we hope to lead the students further onwards to the idea that whenever necessary a new term can be added to the conservation law. This implies that the law becomes valid for any situation. If the students realize this they have grasped a very useful and true concept of the energy conservation law. In this paper we describe the final educational design which we developed in three rounds. Furthermore we will discuss the results in terms of students’ conceptual development based on the results in one school.

Introduction

In the existing situation in the Netherlands students’ ideas on energy in secondary education are diagnosed as inflexible in formal examination tasks (Borsboom et al., 2008). In current education, the law of energy conservation is taught as an indisputable fact detached from its scientific origin, which may cause the usefulness and validity of the law not to be immediately apparent to students (Borsboom et al., 2008; De Vos et al., 2002). Freudenthal (1991) states that knowledge and ability, when acquired by one’s own activity, stick better and are more readily available than when imposed by others, and thus recommends a guided reinvention approach.

To motivate students and to make them appreciate the relevance and usefulness of science, innovation committees for the exact sciences in the Netherlands have chosen a context-based approach (Eijkelhof et al., 2006). Choosing such an approach brings along two major issues: lack of transfer from one context to another and a difficulty to develop widely applicable, abstract concepts in contexts (e.g. Parchmann et al., 2006). More research is needed on these two issues and the concept of energy conservation illustrates both. If we are able to show we can create a context-based learning trajectory for energy we may be quite sure we can do the same for less abstract concepts as well.

We follow Gilbert in his choice for context as the social circumstances as the most promising interpretation of contexts (cf. Gilbert, 2006): the context decides which knowledge is useful in certain jobs that students may end up doing later on in their lives. This way the usefulness of the law of energy conservation should become apparent to students. We will give our students instructions to perform tasks that people having such jobs would perform as well.

We adhere to Freudenthal’s idea of guided reinvention because we think it helps students to grasp the abstract concept of energy by reinventing it, using their own thoughts and arguments. Guided reinvention is based on mathematics as a human activity and in that sense is closely related to contexts. Ogborn (2012) however states that students will not discover any of the big ideas themselves: the ideas in physics only seem to become more obvious as we get used to them. We can only make those big ideas more familiar to the students, so they will feel they understand them.

The above leads us to the following research questions:

1. Which learning steps can be taken in a teaching-learning strategy to guide students to reinvent the concept of energy conservation within a context-based approach?

2. To which extent are students capable of taking those steps?

The first question will get a tentative answer in the educational design section. The second will be answered in the results section on testing that design.
Educational design

Using design research in three rounds, we have developed an educational design, implementing guided reinvention together with a context-based approach consisting of three separate learning steps.

We assume that for most students it is not possible to reinvent the general law of energy conservation in one go. During the first learning step we hand the students three assignments in which we hope a reinvention of what we call partial laws of energy conservation (e.g. \( \sum m \cdot h = k \)) is inevitable (Logman et al., 2010, 2011). This should show the applicability of the law to the assignment. An example of an assignment is shown in Figure 1.

![An amusement park wants to construct a new rollercoaster but not an ordinary one (see Figure [...]).](image)

They want to shoot the cars from below with a maximum speed of 180 km/h. Along a track the cars will move upwards towards the top only to come down along the other side of it. Of course the amusement park wants to build a rollercoaster as high as possible in which the cars do not get stuck at the top by accident. The amusement park asks an engineering company for advice concerning which height can be reached and how. You work for that engineering company and have to come up with at least one feasible solution. Of your solution as many details as possible should be clear, so the amusement park can estimate how much effort (and money) the construction will cost.

1. Design, in groups of 2, the rollercoaster in such a way that you can tell the amusement park which is the maximum height possible according to your design. Discuss your solutions well and work as structured as possible. [..]
2. Subsequently you will have to test your plan on scale to see whether it will work and to resolve uncertainties. [..]
3. Write a report on your laboratory test and draw conclusions from it for the amusement park. [..]

Figure 1. Third assignment set in a technological design context

The students were asked to write an advice report on their solutions like design engineers. We used these reports to assess whether the students succeeded in reinventing the intended laws and whether they thought the laws applied to their solution to the assignment.

In a second learning step we handed the students assignments in which they were asked to come up with experiments that connect two partial laws which would help them to write propositions on whether it is possible to combine the involved partial laws into a more general conservation law. The first assignment they got in this stage of the learning trajectory is shown in Figure 2.

10 If one extracts laws from experiments involving only gravitational energy one will not add the gravitational acceleration \( g \) into this equation because it has no use. \( k \) is only a constant when there is little friction and all other forms of energy are constant. It may vary over different experiments.
During this assignment, demonstrations of a connecting experiment prepared by the teacher were shown, from which the combination of the involved partial laws was to be deduced by the students (e.g. combining \( \sum m \cdot h = k_1 \) with \( \sum m \cdot c \cdot T = k_2 \) to form \( \sum m \cdot h + 426 \cdot \sum m \cdot c \cdot T = k_3 \)). We asked the students to write a report like scientists substantiating their propositions on possible combinations of the partial laws in question. Again we used the reports to assess whether the students succeeded in the appropriate combinations of laws and whether they thought that the combined laws were more widely applicable. The last step involves analyzing the combination process so we wanted the students to reflect on this process and asked them whether it is always possible to find a new term whenever one is needed (Figure 3).

Figure 2. Fourth assignment set in a scientific context

11 The “c” in this equation describing the mixing of various hot and cold substances denotes the specific heat of a substance but not in SI units. Historically c was chosen to be 1 (kcal/kg∙K) for water. \( k_j \) is only a constant when the experiment is well insulated and all other forms of energy are constant. This coefficient is different for different experiments.

12 The specific heat \( c \) is here chosen to be 1 (kcal/kg∙K) for water. The factor 426 (m/K) stems from Joule’s experiment establishing the mechanical equivalent of heat. The coefficient \( k_j \) is only a constant when the experiment has only friction in places where the temperature is measured. Again all other forms of energy need to be constant and the coefficient \( k_j \) may vary over different experiments.

Figure 3. Final assignment set in a scientific context
We are aiming at the students reinventing the general law of energy conservation by arriving at the assumption that combining a new term into the law is always possible when needed. This matches Feynman’s blocks from his Dennis the Menace story in his introduction to energy conservation: in situations that energy appears to be missing such a student will look for a missing term in the law (Feynman et al., 1963). A positive answer would make the conservation law generally applicable. To find out what our students’ opinions were after this reflection process we again asked them to write a scientific report to substantiate their opinions. An overview of the three planned learning steps and their conceptual goals are shown in Figure 4.

Figure 4. Intended learning trajectory towards the general law of energy conservation

For the students to be able to take learning step b at least two partial laws need to be reinvented. To be able to take the final learning step c, in our opinion the students need to perform at least two combinations and therefore at least three partial laws need to be reinvented. Bearing this in mind we chose to have the students reinvent in total four partial laws of energy conservation (4x learning step a) and combine them into an ever more general law in three separate steps, adding one term at a time (3x learning step b). During the last of these three combinations the students were to reflect upon the combination process and check whether the steps needed in that process can always be performed (1x learning step c).

We have developed this material in 3 rounds in 7 different schools in the vicinity of Amsterdam. The material replaces the quantitative introduction of energy. The students worked on the material in groups of two or three. In this paper we discuss the results of 13 groups of sixteen-year-olds of the teacher that tried the material most recently. To save time, about half the groups took on assignment two and the other half took on assignment three. Both assignments were discussed afterwards to make sure all the students were informed about them. During the fifth assignment one of the groups split into two to recombine with another group during the last assignment. Learning step c has only been tested during the last two rounds.

Results

In this section we present the students’ achievements per learning step (see Figure 4).

In the first learning step the first of three assignments was to design a lifting apparatus to lift a capstone on top of pillars in ancient Greece. While the researchers expected four types of solutions involving either pulleys, gears, reels, or levers our students proved to be very ingenious and surprised us by coming up with solutions like steam engines, scissor lifts, hot air balloons, hydraulics, and pneumatics. Figure 5 shows some examples.

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1 The equation at the bottom right is meant to describe the general law of energy conservation including any terms as yet unknown to the students.
The experiments that students came up with during the second assignment of designing a thermostatic water tap showed less variety. There was more variety in how students tried to predict the outcome. These varieties reflected in the laws that students came up with (Figure 6).

During the lessons most groups of students could be guided to come up with a physical law equivalent to the one desired. However, only about half of them used that law in their advice reports and only about a third of the reports showed the derivation of that law from measured data (see Table 1). After a classroom discussion on the reports the students agreed that the reports containing an appropriate law described a better solution than those without. In the third assignment on a rollercoaster a quadratic relationship was to be extracted (see Figure 4) which posed an extra mathematical challenge to our students (Logman et al., 2012).

We interpret these results to distinguish between those students that at this point in the learning process grasped the concept well enough to find it useful to their solution (54%) and those amongst them that positively showed they were capable of reinventing the partial laws themselves (35%).

The next set of assignments asked the students whether it is possible to combine the three reinvented partial conservation laws into one.

This involves combining the laws \( \sum m \cdot h = k_1 \), \( \sum m \cdot c \cdot T = k_2 \), and \( \sum \frac{1}{2} v^2 + \sum g \cdot h = k_4 \) into one law. Given that the laws look similar, students were asked to come up with connecting experiments. For the first combination an experiment involving height and temperature was needed, for the second an experiment involving velocity and either height or temperature. Eleven out of thirteen groups succeeded in describing experiments for the first combination, and all groups succeeded in describing experiments for the second. Apparently the students were able to envision situations in which a combined law would be applicable.

For the first combination the teacher now showed the students a demonstration of Joule’s experiment (Figure 7).
To end up with the right proportionality constant between the two terms in the law of energy conservation we gave the students Joule’s original measurements (Joule, 1850). This led to the following law:

\[-(m_1 \Delta h_1)/(m_2 \cdot c_2 \cdot \Delta T_2) = 426\text{ m/K}\]

After some rewriting guided by the teacher and expanding the law to multiple objects this resulted in:

\[\sum m \cdot h + 426 \cdot \sum m \cdot c \cdot T = k_3\]

Using the quadratic relationship from the rollercoaster experiment (see Figure 4) in a similar way the term containing velocity was added:

\[\sum m \cdot g \cdot h + 426 \cdot g \cdot m \cdot c \cdot T + \sum \frac{1}{2} \cdot m \cdot v^2 = k_5\]

About 90% of the students could be guided to find the combined law and use it in their scientific report (see Table 2). However, about three quarter of them did not derive the combined law.

Table 2. Overview of the results for the fourth and fifth assignment

<table>
<thead>
<tr>
<th>Report contains</th>
<th>Assignment 4</th>
<th>Assignment 5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appropriate combination</td>
<td>11/13 (85%)</td>
<td>13/14 (83%)</td>
<td>24/27 (89%)</td>
</tr>
<tr>
<td>Derivation of combination</td>
<td>3/13 (23%)</td>
<td>4/14 (29%)</td>
<td>7/27 (26%)</td>
</tr>
</tbody>
</table>

Again we interpret these results to distinguish between those students that at this point in the learning process grasped the concept well enough to find it useful to their solution (89%), and those that positively showed they were capable of repeating the combination of the partial laws themselves (26%). However, during these two assignments the students were guided to such an extent by the teacher that we cannot be sure that they really had these capabilities at this point in the learning process. The last assignment aimed at extrapolating the combination process to the idea that whenever necessary a new term can be added to the conservation law. At this stage the students were asked how far the process of combining can be extended and how many terms can be added to the law. Again students were asked for connecting experiments but now had to pinpoint the new characteristic variable as well. The experiments students came up with again were numerous, showing the possible size of the applicability domain of a combined law. For all of the experiments the students could identify the characteristic variable. However, to do so, in cases involving electricity or muscles the teacher had to ask which quantity in the source decreased, leading the students to fuel, ATP, and wind speed amongst others.

At this point the students received a description and data from a fictitious experiment which connects the electric potential energy \((\frac{1}{2} \cdot C \cdot U^2)\) of a capacitor to an already known form of energy (thermal energy). During the combination process the students were asked whether the steps taken can always be performed when necessary. Again the students had to substantiate their findings in a report.

\[14\text{ The constant } c \text{ was earlier chosen to be } 1\text{ (kcal/kg⋅K) for water. A new constant } c^* \text{ can be defined as } 426 \cdot g \cdot 1 = 4180\text{ (J/kg⋅K): the specific heat of water.}\]
About three quarter of our students showed in their reports that they knew how to derive the new partial law of energy conservation involving $U$ and $T$ (see Table 3). However, only two groups out of 13 managed to combine this new partial law into the already established law. Only one group compared the predicted combination process steps to the steps taken to form a substantiated opinion on whether the law could be expanded whenever needed. After being given the appropriate combination seven more groups were convinced that the law could be expanded whenever needed even though most of them were not capable themselves of adding the new law to the already established law.

**Table 3. Overview of the results for the final assignment**

<table>
<thead>
<tr>
<th>Report contains</th>
<th>Assignment 6a: Extracting new law</th>
<th>Assignment 6b: Combining new law</th>
<th>Assignment 6c: Extrapolating combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appropriate law</td>
<td>12/13 (92%)</td>
<td>2/13 (15%)</td>
<td>8/13 (62%)</td>
</tr>
<tr>
<td>Derivation of law</td>
<td>10/13 (77%)</td>
<td>2/13 (15%)</td>
<td>1/13 (8%)</td>
</tr>
</tbody>
</table>

We interpret the results in a similar way as before. The number of students that positively showed that they were capable of reinventing a new partial law of energy conservation themselves has grown from 38% (see Table 1) to 77% at this stage in the learning process. However, adding the new law and extrapolating the combination process on their own remained hard for our sixteen-year-old students (respectively 15% and 8% only). No less than 92% of our students used the new law in their report and 62% grasped the concept of energy conservation well enough to state in their reports that they believed a new term can always be added to the law even though they did not appear capable of combining the new term into the law themselves. During this last assignment there was only guidance in giving the appropriate combination so we can be quite sure about the reported numbers of students.

**Discussion and conclusions**

The most problematic steps our students encountered on the intended learning trajectory were extracting non-linear (e.g. quadratic) relationships from measured data, combining physical laws, and reflecting on a process. In our approach about three quarter of our students were capable of reinventing a partial law of energy conservation. An even larger part grasped the concept of extracting partial laws of energy conservation well enough to apply it in a new assignment. Guided reinvention combined with a context-based approach nearly solved that part of the problem.

The next step of combining partial laws did remain difficult and only a small portion of our sixteen-year-old students were capable of performing an appropriate combination themselves and recognized its applications. However, asking for such a combination goes beyond the requirements of the Dutch curriculum and probably most other curricula as well.

Ogborn (2012) states that students will not discover any of the big ideas themselves: the ideas in physics only seem to become more obvious as we get used to them. We have to agree and disagree with Ogborn on this. Somewhat more than half our students did become more used to the idea of energy conservation and came to think of it as a useful, valid concept. However, a small percentage of students also proved capable of reinventing one of the big ideas in physics completely. This number is perhaps comparable to the number of students that grasp a true conception of energy conservation in traditional education.

Because in more traditional approaches the usefulness and validity of energy conservation evades many students we are satisfied with the results on extracting partial laws of energy conservation and the way in which the students become more familiar with the general law of energy conservation. However the number of students that are capable of combining partial laws and of reinventing the general law of energy conservation can certainly be improved upon. Having only had two rounds of try-outs that incorporated the final step of reinventing the general law of energy conservation we are convinced that there is room for such improvement within our approach. For example an extra combination could be added to the material and the guidance during the combinations could now be diminished gradually. It is also possible to postpone such combinations to higher classes in which the students are perhaps better equipped to overcome the mentioned problems.
References


