Students reinventing the general law of energy conservation
Logman, P. S. W. M.

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Chapter 6

Summative evaluation of a context-based approach making use of guided reinvention while aiming at a versatile concept of energy

Abstract

In current Dutch education students’ conceptions of energy have been diagnosed as non-versatile. This may be due to the fact that the concept of energy is taught as an unsubstantiated, ready-made concept. For mathematics a similar problem has been observed by Freudenthal and he recommends a guided reinvention approach to resolve it.

Because the new Dutch curriculum for the exact sciences advises a context-based approach in three try-outs we have designed a teaching-learning sequence that combines such an approach with guided reinvention to develop a versatile conception of energy conservation. The concept of energy conservation is developed in three consecutive learning steps each aiming at a different level of versatility. With our teaching-learning sequence we aim at sixteen- or seventeen-year-old pre-university students.

This article contains the summative assessment of students’ versatility levels from the third and final try-out of our approach and uses the consecutive learning steps to assess those levels. It also gives results for the applicability of the conceptions students developed in the learning process and defines very near, near, and far transfer questions to do so.

Because the three conceptual learning steps build upon one another the level of try-out is different for each step. For the first level of versatility satisfactory results have been achieved (about two thirds of our students managed to take the corresponding conceptual learning step). For the next two levels recommendations are given. For applicability the results are comparable to applicability results for eighteen-year-old Dutch exam students in traditional education.

1 This chapter has been submitted for publication as Logman, P. S. W. M., Kaper, W. H., & Ellermeijer, A. L. (2014). Summative evaluation of a context-based approach making use of guided reinvention while aiming at a versatile concept of energy.
6.1 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). A similar problem has been observed earlier with students attending university chemistry courses on thermodynamics (Kaper, 1997). 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; Doménech et al., 2007; Liu et al., 2002; De Vos et al., 2002; Kaper, 1997; Driver & Warrington, 1985).

A very different approach to teaching the concept as an indisputable fact is to guide the students in reinventing the concept themselves. 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 recommends a guided reinvention approach. Aiming at contributing to a solution to the afore-mentioned problem we have designed a new teaching-learning strategy for the concept of energy conservation making use of guided reinvention. We have developed the initial steps of this innovative approach using the design research method (Van den Akker, 2006) in three try-outs.

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).

To reinvent the concept of energy several subsequent conceptual learning steps need to be taken by the students: deriving physical laws from measurements, manipulating those physical laws in order to combine them, and reflecting on the procedure which is needed to combine such physical laws. This learning process resembles real science much closer than the traditional teaching of the subject.

The success of each conceptual learning step in our strategy depends on the results of the earlier conceptual learning steps. Investigating whether our extensive trajectory would be possible for students to follow was therefore done one step at a time as well. Because of this the learning steps in our teaching-learning strategy are each at a different level of try-out.

In this article we will investigate to which extent the various generalizations were achieved and whether the students were able to apply their resulting conceptions to situations from the corresponding domains. Our research question is therefore the following:

To which extent are students able to generalize in order to reinvent the general law of energy conservation and to which extent are they able to apply the resulting concepts?
In this article we will first give a short summary of our final educational design, followed by our research questions for this article. Then the instruments and analysis method are described, followed by a presentation of our results. The article ends in answering our research questions and discussing those answers in the light of the new Dutch physics curriculum.

6.2 Educational design

In this section we will clarify the choices we made in implementing our teaching-learning strategy. This section is a summary of an elaborate description of our educational design rationale (Logman et al., submitted-a).

Curriculum innovation committees for the exact sciences in the Netherlands have advised a context-based approach (Commissie Vernieuwing Natuurkunde onderwijs havo/vwo, 2006). The revised curriculum will result in new national exams in 2016. Using a context-based approach brings along two major challenges: how to achieve transfer from one context to another (Goedhart et al., 2001; Parchmann et al., 2006; Schwartz, 2006) and how to develop abstract concepts within such an approach (Parchmann et al., 2006; Pilot & Bulte, 2006; Schwartz, 2006).

These two challenges are similar to the issues in traditional teaching of the concept of energy as described in the introduction. Energy is an abstract concept and lack of transfer may obstruct the applicability of a student’s conception of it. To address these challenges we decided to use a guided reinvention approach as recommended by Freudenthal (1991).

For our implementation of guided reinvention we assume that for most students it is not possible to reinvent the general law of energy conservation in one go, which is in line with the historical development of this law (Logman et al., submitted-a). During a first learning step, we hope students to reinvent what we call partial laws of energy conservation each with its own applicability domain (e.g. \( \sum mcT = k_1 \) for insulated mixing of a hot and cold substance).

In a second learning step the students are asked to combine these partial laws into more and more general laws of energy conservation (e.g. combining \( \sum mcT = k_1 \) with \( \sum mgh = k_2 \) to form \( \sum mgh + \sum mcT = k_3 \)). Because it remains possible that new terms will show up, this combination procedure does not lead to a point where one can be sure that the law is complete: the result may still be only a partial law of energy conservation albeit covering an ever larger domain incorporating more and more situations.

At this stage the students need to take a third learning step in which they are to extrapolate the steps needed in the procedure of every combination of laws and check whether those procedural steps are always possible. If the student is able to discuss the necessary steps and arrives at the conclusion that combining a new term into the law is always possible when needed, in the student’s mind the law must now have become applicable to any situation and can therefore truly be called general (as opposed to partial): the general law of energy conservation...
has been reinvented (as an axiom). If students, however, arrive at the conclusion that combining a new term into the law may not always be possible, they should now be able to discuss their conclusion.

Every time that in the course of steps I, II, and III the students revise their conception successfully, the students generalize their conception from specific situations via expanding domains to in the end possibly being able to apply it to any situation, thus developing a widely applicable, abstract conception of energy.

An overview of the three necessary learning steps and their conceptual goals is given in Table 6.1.

<table>
<thead>
<tr>
<th>Learning step</th>
<th>Conceptual goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>I: Reinvent a partial law of energy conservation.</td>
<td>e.g. $\sum mcT = k_1$</td>
</tr>
<tr>
<td>II: Combine partial laws of energy conservation.</td>
<td>e.g. $\sum mgh + \sum mcT = k_3$</td>
</tr>
<tr>
<td>III: Extrapolate the combination procedure through reflection.</td>
<td>$\sum mgh + \sum mcT + \sum \frac{1}{2}mv^2 + \ldots = k_4^2$</td>
</tr>
</tbody>
</table>

In our teaching-learning strategy we have chosen to have the students reinvent a total of five partial laws of energy conservation (five times learning step I: see left column in Figure 6.1) and combine them in three steps into an ever more general law adding one term at a time (three times learning step II: middle column in Figure 6.1). During the last of these three combinations the students are to reflect upon the combination procedure and check whether the steps needed in that procedure can always be performed (one time learning step III: right column in Figure 6.1) (Logman et al., submitted-a).

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2 Meant to describe the general law of energy conservation including any as yet unknown terms to the students.
Figure 6.1 An overview of the conceptual development.

We have created three technological design problems to establish three partial laws of energy conservation by taking conceptual learning step I three times (see Table 6.2). The students worked on these problems in couples. For each problem the couples were given worksheets to guide them through the design process ending in writing an advice report on their solution to the problem. Every couple worked on assignment 1, while about half the couples were given assignment 2 and the other half were given assignment 3.

Table 6.2 Examples of technological design assignments

<table>
<thead>
<tr>
<th>Assignment</th>
<th>Technological design assignment</th>
<th>Intended partial law</th>
<th>Learning step</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Design a lifting apparatus.</td>
<td>$\sum m_h = k_5$</td>
<td>I (domain A)</td>
</tr>
<tr>
<td>2</td>
<td>Design a thermostatic mixer tap.</td>
<td>$\sum m_c T = k_6$</td>
<td>I (domain B)</td>
</tr>
<tr>
<td>3</td>
<td>Design a rollercoaster.</td>
<td>$\sum g h + \frac{1}{2} v^2 = k_7$</td>
<td>I (domain AC)</td>
</tr>
</tbody>
</table>

To take conceptual learning steps II and III the students were given three more assignments. These assignments were set in a scientific context. During the first and last of these scientific assignments another partial law was to be reinvented (conceptual learning step I). We chose to embed these conceptual learning steps I in the scientific assignments. Due to the fact that it was new to the students during assignments 4 and 5 the teachers were asked to show the students how to take conceptual learning step II in a classroom discussion. During the final assignment 6 the students should be able to take both conceptual learning steps I and II by themselves and reflect on the procedure involved in those two learning steps. This reflection encompasses conceptual learning step III.
Again for each problem the students were given worksheets to guide them through the scientific process ending in writing a scientific report.

Table 6.3 Examples of scientific assignments

<table>
<thead>
<tr>
<th>Assignment</th>
<th>Scientific research questions</th>
<th>Intended law</th>
<th>Learning steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Do experiments exist in which ( h ) increases and ( T ) decreases or the other way around? If so, could a new law describing such an experiment describe all experiments so far?</td>
<td>( \sum mgh + \sum mcT = k_3 )</td>
<td>I (domain AB), II (domain AB)</td>
</tr>
<tr>
<td>5</td>
<td>Can the law for the rollercoaster be incorporated in the same manner?</td>
<td>( \sum mgh + \sum mcT + \sum \frac{1}{2}mv^2 = k_9 )</td>
<td>II (domain ABC)</td>
</tr>
<tr>
<td>6</td>
<td>How many more terms can be added to the law?</td>
<td>( \sum mgh + \sum mcT + \sum \frac{1}{2}mv^2 + \cdots = k_9^3 )</td>
<td>I (domain BD), II (domain ABCD), III (meta concept)</td>
</tr>
</tbody>
</table>

An overview of the chronology in which the students were given the various assignments is given in Figure 6.2.

![Figure 6.2 An overview of the six assignments combining the nine conceptual learning steps.](image)

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3 Meant to describe the general law of energy conservation including any as yet unknown terms to the students.
6.3 Research setup

6.3.1 Research questions
Our research question as given in the introduction can be subdivided in questions about students’ ability to generalize (revisability) and about students’ ability to apply the resulting laws to various situations (applicability).

Each conceptual learning step of the designed learning trajectory (see Table 6.1) is intended to generalize students’ conceptions of energy conservation, widening its applicability domain with each step. The question to which extent students are able to generalize physical laws in order to reinvent the general law of energy conservation can thus be subdivided per conceptual learning step:

I. To which extent are students able to generalize single observations into a (quadratic) quantitative law (conceptual learning step I)?

II. To which extent are students able to combine two earlier understood laws of physics into a new one that is more widely applicable than the two original laws together (conceptual learning step II)?

III. To which extent are students able to generalize the combination procedure and extrapolate it into a metaconcept ideally comprising the general law of energy conservation (conceptual learning step III)?

An additional question is whether students are able to apply their conception of energy conservation to various situations:

IV. To which extent are students able to apply their concept of energy conservation to various situations from various domain parts?

In answering this question we will also reflect on how students that followed our teaching-learning sequence perform against the 2016 Dutch exam requirements for the upcoming curriculum (van Weert et al., 2012: for a translation in English see Appendix A).

6.3.2 Experimental groups
With our teaching-learning strategy we aim at pre-university level sixteen- or seventeen-year-olds who have little or no quantitative knowledge about the concept of energy. In the Netherlands the exam program for secondary education informs teachers of the content of the curriculum but it is up to the teacher to decide when and how to teach the various subjects. This made it possible to test our material with different age groups. During our final try-out the material was tested in 4 classes of students from 3 different schools in the Amsterdam region. In the first school the researcher himself taught a class of sixteen-year-olds. In the second school 2 teachers taught 2 classes of seventeen-year-olds and in the third school 1 teacher taught 1 class of sixteen-year-olds.
Table 6.4 An overview of the experimental classes

<table>
<thead>
<tr>
<th>Class</th>
<th>School</th>
<th>Teacher</th>
<th>Age</th>
<th>Number of students</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>School 1</td>
<td>Researcher</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>School 2</td>
<td>Teacher 1</td>
<td>17</td>
<td>29</td>
</tr>
<tr>
<td>3</td>
<td>School 2</td>
<td>Teacher 2</td>
<td>17</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>School 3</td>
<td>Teacher 3</td>
<td>16</td>
<td>27</td>
</tr>
</tbody>
</table>

Due to specific circumstances only 10% of the students in class 3 handed in their worksheets and final reports for assignment 6. Because this assignment contains our main possibility to perform our final assessment of the three conceptual learning steps we discarded this class from our analysis.

6.3.3 Instruments

In this section we describe which instruments were used to answer the research questions. In Section 6.4 the analysis criteria are given per research question. Having focused on conceptual learning step I during the first two try-outs (Logman et al., 2010, 2011) we now shifted our focus to conceptual learning steps II and III.

To answer the first three research questions on the learning process we gave the students specific worksheets for crucial steps in that process. During assignment 6 we inserted a worksheet specifically to determine students’ final capabilities in taking conceptual learning step I.

To determine students’ final capabilities in taking conceptual learning step II a subsequent worksheet was inserted during assignment 6. Besides that, to have a second assessment of this learning step, we added a question to a test given about a week after the teaching-learning sequence. In this question the students individually and in an exam setting were given a new partial law of energy conservation and were asked to combine it into the already established law.

To determine students’ success in taking conceptual learning step III the students had to answer the final scientific problem in a report. To have a second assessment of this learning step we asked the students again about their views on the extrapolation of the combination procedure in one of the questions during a survey a few weeks after the teaching-learning sequence.

To answer the last research question on students’ abilities to apply their conception of energy, we added problems from various domains (investigated and uninvestigated) into the final individual test. To analyze whether the students had retained their knowledge and to be able to compare them to others we gave the students the Energy Concept Inventory, or ECI (Swackhamer & Hestenes, 2005). The ECI was answered individually several months after the teaching-learning sequence and mostly in the next grade. We also tracked whether the students applied their newly reinvented partial law of energy conservation in their advice reports to technological design assignments 1, 2, and 3.
Table 6.5 shows an overview of the use of the various instruments in answering the research questions.

<table>
<thead>
<tr>
<th>Research question</th>
<th>Advice report 1</th>
<th>Advice report 2</th>
<th>Advice report 3</th>
<th>Worksheet H(^4) in assignment 6</th>
<th>Worksheet I(^5) in assignment 6</th>
<th>Scientific report 6</th>
<th>Final test questions 1, 2, 3, &amp; 4</th>
<th>Final test question 5</th>
<th>Energy Concept Inventory</th>
<th>Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. To which extent are students able to generalize single observations into a (quadratic) quantitative law (conceptual learning step I)?</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II. To which extent are students able to combine two earlier understood laws of physics into a new one that is more widely applicable than the two original laws together (conceptual learning step II)?</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>III. To which extent are students able to generalize the combination procedure and extrapolate it into a meta concept ideally comprising the general law of energy conservation (conceptual learning step III)?</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV. To which extent are students able to apply their concept of energy conservation to various situations from various domain parts?</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

**6.4 Analysis criteria per research question**

In this section we will discuss our criteria based on which we classified students as fulfilling the intentions of each research question. We will illustrate our criteria with a description of the desired answer. During the learning process the students worked in couples, however at the end some activities were done individually to determine individual learning outcomes.

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\(^4\) Worksheet 6H as described elsewhere (Logman et al., submitted-a).

\(^5\) Worksheet 6I as described elsewhere (Logman et al., submitted-a).
6.4.1 Research question I on conceptual learning step I

During assignment 6 we asked the couples to find the law that describes given measurements from a fictitious experiment involving a capacitor and an insulated resistor connecting the variable temperature to the variable voltage. The couples were given the data shown in Table 6.6.

Table 6.6 Fictional experimental data from assignment 6

<table>
<thead>
<tr>
<th>$U_{\text{capacitor, begin}}$ (V)</th>
<th>$U_{\text{capacitor, end}}$ (V)</th>
<th>$T_{\text{resistor, begin}}$ (°C)</th>
<th>$T_{\text{resistor, end}}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>18.0</td>
<td>18.0</td>
</tr>
<tr>
<td>1.0</td>
<td>0.0</td>
<td>18.0</td>
<td>18.1</td>
</tr>
<tr>
<td>2.0</td>
<td>0.0</td>
<td>18.0</td>
<td>18.2</td>
</tr>
<tr>
<td>3.0</td>
<td>0.0</td>
<td>18.0</td>
<td>18.5</td>
</tr>
<tr>
<td>4.0</td>
<td>0.0</td>
<td>18.0</td>
<td>18.9</td>
</tr>
<tr>
<td>5.0</td>
<td>0.0</td>
<td>18.0</td>
<td>19.4</td>
</tr>
</tbody>
</table>

The idea was for the couples to reinvent a quadratic relationship by linearizing the data in a graph. This results for example in the two graphs shown in Figure 6.3.

Figure 6.3 Examples of graphs drawn from the fictional data from assignment 6; normal axes (top) & linearized axes (bottom).
The couples were now expected to write down the linear equation (1) describing the graph:

\[
\frac{\Delta T}{\Delta U^2} = \frac{-1.4}{25} = -0.056
\]  

(1)

After finishing this step, the worksheets of the couples had to be collected by the teacher because in the next worksheet the resulting law was given (although without a calculation). In some classes however the worksheets were not collected at this point, so to be safe we only classified those couples as successful that explicitly calculated the constant in their derivation of this partial law.

As a result we set the following criteria to assess whether couples are capable of taking conceptual learning step I. The couples had to show:

- an extended table or a linearized graph of the given data,
- the derivation of the correct partial law of energy conservation from that data, including,
- the calculation of the constant for that partial law of energy conservation.

### 6.4.2 Research question II on conceptual learning step II

During assignment 6 the couples were given the new partial law (equation (1)) in a subsequent worksheet and were asked to combine the new law into the law with which we ended up after assignment 5: equation (2):

\[
\sum mgh_{\text{before}} + \sum mcT_{\text{before}} + \sum \frac{1}{2} m v_{\text{before}}^2 = \\
\sum mgh_{\text{after}} + \sum mcT_{\text{after}} + \sum \frac{1}{2} m v_{\text{after}}^2
\]  

(2)

To do so equation (1) may be rewritten as equation (3):

\[
T_{\text{begin}} + 0.056 v_{\text{before}}^2 = T_{\text{end}} + 0.056 v_{\text{after}}^2
\]  

(3)

This equation may be combined with equation (2) into equation (4):

\[
\sum mgh_{\text{before}} + \sum mcT_{\text{before}} + \sum \frac{1}{2} m v_{\text{before}}^2 + \sum 0.056mcU_{\text{before}}^2 = \\
\sum mgh_{\text{after}} + \sum mcT_{\text{after}} + \sum \frac{1}{2} m v_{\text{after}}^2 + \sum 0.056mcU_{\text{after}}^2
\]  

(4)

Knowing the mass \((m = 0.0050 \, \text{kg})\) and the specific heat \((c = 850 \, \text{J/(kg°C)})\) of the resistor and the electrical capacitance \((C = 0.47 \, \text{F})\) of the capacitor some couples came up with a term \(\frac{1}{2} C U^2\) instead of \(0.056mcU^2\). Although this is correct in this situation, it would take a generalization over more experiments than just the one from which the data was given. These extra experiments would require varying the mass of the resistor, the specific heat of the resistor, and the electrical capacitance of the capacitor. Only after inspecting data from such
experiments it would be possible to verify that $\frac{1}{2}CU^2$ should be the new term in the conservation law. Therefore both $\frac{1}{2}CU^2$ and $0.056mcU^2$ were considered correct solutions for the new term.

Our criteria to assess whether couples are capable of taking conceptual learning step II during assignment 6 are that couples:

- describe a derivation of the new term either generalized completely ($\frac{1}{2}CU^2$) or limited to the materials used in the given experiment ($0.056mcU^2$),
- combine all earlier terms including the new term in one law, and,
- use a summation over each type of term (form of energy) thereby implying a generalization over an indefinite number of objects.

A second source to assess conceptual learning step II was question 5 in the final test, alongside several more quantitative test questions. To have a spare one for students that were ill during the final test we created two versions of it. This time each student individually had to establish the new term for a new form of energy from a given partial law of energy conservation. To be able to do so they now had to perform the necessary steps from memory.

In the final test the students were given the fifth question from Figure 6.4 or a very similar one in the other version of the test.

A new term

On a stove we heat up 2.5 kg of water ($c_{\text{water}} = 4180 \text{ J/(kg} \cdot \text{K})$) to various temperatures, as isolated as possible, and measure how much gas is burned to accomplish that. In our results we compensate for heating the pot itself. From our results it follows that $\Delta T/\Delta V = -3029 \text{ } ^o\text{C/m}^3$.

Try to establish which term needs to be added to our conservation law using this result.

Figure 6.4 An example of question 5 from the final test.

A perfect answer derived in a similar way as before would give $3.2 \cdot 10^7 \cdot V$ as the new term in the conservation law in which $3.2 \cdot 10^7$ equals the heating value of methane ($r_V$). Students that did not take into account the number of significant figures at this stage, thus coming up with $31,653,050 \cdot V$, were excused and seen as being able to combine the law anyway. Students that came up with the term $3029 \cdot mcV$ (not generalizing the law towards any mass of water and

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6 The given partial law could be rewritten as:

$$T_{\text{before}} + 3029 \cdot V_{\text{before}} = T_{\text{after}} + 3029 \cdot V_{\text{after}}.$$  

This equation in its turn leads to:

$$\sum mgh_{\text{before}} + \sum mcT_{\text{before}} + \sum \frac{1}{2}mv_{\text{before}}^2 + \sum 3029 \cdot mcV_{\text{before}} =$$

$$\sum mgh_{\text{after}} + \sum mcT_{\text{after}} + \sum \frac{1}{2}mv_{\text{after}}^2 + \sum 3029 \cdot mcV_{\text{after}}.$$  

In this equation $3029 \cdot mcV$ becomes $31653050 \cdot V$ by using the constants given in the test question.
any type of substance because data from experiments in which those were varied were not available) were also identified as understanding the steps necessary to combine the new law into the earlier established conservation law. Summarizing, our criterion to assess whether students were capable of taking conceptual learning step II during the final test question 5 is that students:

- describe a derivation of the new term either generalized completely \((31,653,050 \cdot V)\) or limited to the materials used in the given experiment \((3029 \cdot mcV)\).

### 6.4.3 Research question III on conceptual learning step III

Two types of students were classified as being able to take conceptual learning step III:

- students that discussed all the necessary procedural steps and as a result of that came up with the idea that an addition is always possible, and,
- students that discussed one of the necessary procedural steps and as a result of that came up with the idea that an addition may not always be possible.

We classified the students at two moments: during assignment 6 and in the survey afterwards.

Working in couples during assignment 6 students were asked how many terms could be added to the conservation law. To find out they were asked to reinvent a new partial law from given data and combine it into the earlier established conservation law. During this procedure they were to pay attention to which steps are necessary and whether those steps are always possible or not, in order to be able to make a statement on how many terms can be added and to make proposals which terms can be added.

We wanted couples to discuss the necessary procedural steps for adding a new term to the conservation law (see Table 6.7).

#### Table 6.7 Procedural steps during conceptual learning step III requiring discussion

<table>
<thead>
<tr>
<th>Procedural step</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Identify characteristic quantity.</td>
</tr>
<tr>
<td>2 Measure new quantity in relation to one of the already established quantities.</td>
</tr>
<tr>
<td>3 Establish relationship between those two quantities.</td>
</tr>
<tr>
<td>4 Rewrite the law into a notation in which before and after are moved to either side of the equation.</td>
</tr>
<tr>
<td>5 Multiply the whole equation by selected constants to make the term containing the already known quantity equal to a term appearing in the already established (now partial) law of energy conservation.</td>
</tr>
<tr>
<td>6 Add the term containing the new quantity to the already established law of energy conservation expanding it to include the phenomenon encountered.</td>
</tr>
<tr>
<td>7 Add sigma’s to each term to generalize over more than one object for each type of term (i.e. for each form of energy).</td>
</tr>
</tbody>
</table>
Summarizing, our criteria to assess whether couples are capable of taking conceptual learning step III, are that it is clear that couples:

- discuss all seven procedural steps on whether they are always possible and thereby arriving at a positive answer, or
- express hesitations on the possibility of taking one (or more) of the procedural steps.

During the survey several weeks after the teaching-learning sequence students were individually given a question on whether they thought the law of energy conservation would be applicable to any situation and to explain their answer. To expect a complete answer in this case would be a lot to ask from the students but, to keep the two measurements comparable, we decided to use the same strict criteria as above. To indicate how far students reached towards such a full discussion of all procedural steps we decided to also count the number of discussed procedural steps in their answers. This analysis of conceptual learning step III also indicated to which extent students would be willing to revise their conception of energy in future learning about the concept and thus indicated that aspect of their conception’s versatility as well.

6.4.4 Research question IV on concept applicability

To measure the extent to which students are able to apply their concept of energy conservation to situations from various domain parts we define three levels of transfer: very near, near and far.

Very near transfer is achieved when student couples apply their partial laws of energy to the same problem as from which they derived the law. This can be seen from their worksheets and advice reports.

Near transfer is achieved when students apply the partial laws of energy conservation they reinvented themselves during technological design assignments 1, 2, and 3 (respectively $\sum mh = k_s$, $\sum mcT = k_6$, and $\sum gh + \frac{1}{2}v^2 = k_7$) to other problems within the respective domains. These domains concern respectively gravitational energy, thermal energy, and a combination of gravitational and kinetic energy. To test this transfer we created three test questions: one for each domain part addressed (see Appendix B for examples). These were given to the students individually during the final test.

Far transfer is achieved when students apply the combined law of energy conservation to domain parts that were not addressed earlier in the technological design assignments. To test this we added one test question to the final test. This question involved a combination of gravitational, thermal, and kinetic energy (see Appendix C for an example).

To have a spare test for students that were ill during the final test we created two versions of both the near and far transfer questions.

To be able to compare transfer results from these questions to earlier results from our preliminary research in exam classes we used the less quantitative Energy Concept Inventory (Swackhamer & Hestenes, 2005). The ECI was given to
the students individually several weeks after the teaching-learning sequence had ended. We selected those questions as near transfer questions that addressed the same domains as described above as near transfer domains (ECI questions 2, 4, 26, 27, 32, and 34). The questions from the Energy Concept Inventory that were not selected as near transfer questions were used to test far transfer. Below we will describe the criteria we used to classify the students in attaining the various levels of transfer.

**Very near transfer**
The criterion we used to classify couples as having attained very near transfer was the following:
- Couples that actually made a calculation using the derived concept in one of their worksheets or advice reports during the technological design assignments.
We did not require the couples to be able to apply the concept in all their technological design assignments. This is because some couples may not have seen the need to apply their conception to problems in every assignment.

**Near transfer**
Our criterion to classify students as having attained near transfer is the following:
- Students that answered the test questions on near transfer without a conceptual mistake (minor calculation mistakes were allowed).
The first of the three questions in each test could also be solved by the law of the lever and was for that reason disregarded in our final analysis. We used the average of students’ results over the two remaining questions as one indicator for their achievements for near transfer. We did the same for the six selected ECI questions to produce a second indicator.

**Far transfer**
We used the same criterion to classify students as having attained far transfer:
- Students that answered the test question on far transfer conceptually correct (again minor calculation mistakes were allowed).
For the ECI questions classified as far transfer questions we again averaged students’ results for those questions.

### 6.5 Results

In this section we will present our results for each research question.

#### 6.5.1 Conceptual learning step I

Counting those couples that showed a clear derivation of the quadratic law we found that 64.7% of our 34 couples of students were capable of taking this step during assignment 6.
Five couples did not hand in their worksheets (14.7%). There were six couples that wrote down the correct solution but did not meet our strict criterion of showing a complete derivation (17.6%). These six couples were all from one class (school 3) in which the subsequent worksheet containing the answer was handed to the couples before they had finished the worksheet in which they had to derive the partial law. One couple (2.9%) assumed that the desired relationship would be linear and only used one measurement out of the five given in the fictitious experiment.

The main issues left were thus couples not handing in their worksheets, a teacher giving the subsequent worksheet too soon, and couples assuming relationships to be linear. In the first two issues the intended learning path was not followed correctly. The last issue needs a further response to be implemented in our teaching-learning sequence. The lower results from school 3 considerably influenced the overall results. Where school 3 scored only 46.2% (n=13) for this conceptual learning step, the other two schools scored 83.3% (n=6) and 73.3% (n=15). Leaving school 3 out would have resulted in a 76.2% score instead of a 64.7% score which indicates a higher score for conceptual learning step I may be feasible.

6.5.2 Conceptual learning step II

Counting those couples that did combine the given partial law into the earlier combined law of energy conservation within our requirements we found that 32.4% of our couples (n=34) were capable of taking conceptual learning step II during assignment 6.

The majority of couples (52.9%) did not combine the partial laws into one law. They did not get beyond the point in the combination procedure in which the partial law is rewritten into a notation in which before and after are moved to either side of the equation (e.g. Figure 6.5).

\[ T_{voor} + 0.06U^2_{voor} = 0.06U^2_{na} + T_{na} \]

Figure 6.5 A couple’s resulting law: “\( T_{\text{before}} + 0.06U^2_{\text{before}} = 0.06U^2_{\text{after}} + T_{\text{after}} \)”.

They did not generalize over multiple objects by adding a summation over each term and they did not combine all terms into one law. One couple (2.9%) did generalize over multiple objects (capacitors and resistors) and only forgot to combine all terms into one law (see Figure 6.6).

\[ \sum \Delta U_c^2 + \sum \Delta T_c = \sum \Delta U_R^2 + \sum \Delta T_R \]

Figure 6.6 A couple’s resulting law: a generalization over multiple objects.

Then there were two couples (5.9%) that found the right term to add to the earlier combined law but did not write down the law that combines all previously reinvented partial laws (see Figure 6.7).
Chapter 6

\[ cmT + 0.056 \text{ cm}U_{\text{final}} = cmT + 0.056 \text{ cm}U_{\text{end}} \]
\[ \text{Vul} (0.056 \text{ cm}U^2) \text{ in: } 0.056 \cdot 850 \cdot 0.0050 \cdot U^2 = 0.238U^2 \]

Let op: 0.238 is de helft van 0.47 (de C van de condensator), dus dan wordt het \( \frac{1}{2} \cdot C \cdot U^2 = \text{constant} \)

**Figure 6.7 A couple’s elaboration on combining partial laws:**

- substitute \((0.056 \text{ cm}U^2)\): \(0.056 \cdot 850 \cdot 0.0050 \cdot U^2 = 0.238U^2\),
- Note: 0.238 is half of 0.47 (the C for the capacitor), so it becomes \(\frac{1}{2}CU^2 = \text{constant}\).

Finally there were two more couples (5.9%) that did combine all known terms but left out the summation that indicates a generalization over multiple objects (see Figure 6.8).

**Figure 6.8 A couple’s resulting combined law.**

The main issues left are couples ending the combination process prematurely and couples not being able to relate the various aspects of the resulting law to its domain.

In school 3 none of the couples finished the combination process completely. This again influenced the overall results negatively. The other two schools scored 66.7% (n=6) and 46.7% (n=15). Leaving school 3 out would have resulted in a 52.4% score instead of a 32.4% score which indicates a higher score for conceptual learning step II may also be feasible.

During the final test, working individually and without notes, only 5.3% (4 students) were able to perform the combination within our requirements but in each class there was at least one student that was capable of doing so. Of these four students two students previously during assignment 6 had left out the summation over all terms but did find the new form of energy to add. In the individual test they were not asked to give the new combined law but only the new form of energy so this time the summation was not required.

### 6.5.3 Conceptual learning step III

None of the couples gave a full discussion of all the necessary steps in combining a new partial law into the already established law to substantiate their opinion. However several couples (38.2%) were on the right track towards such a discussion and gave one or more arguments about the validity of the law. Most of these couples discussed only one or two steps. Out of these 38.2% there were three couples (8.8%) that discussed six out of the seven necessary steps to combine a new partial law into the already established law.

In their final scientific report 64.7% of the couples stated that they were convinced that whenever necessary a new form of energy could be added to it (5.9% were hesitant and kept their reservations). None of the couples explicitly stated that it would not be possible to add a new form of energy when necessary. There were several couples that did not hand in their final reports (20.6%) while four other couples did not formulate an answer to the question about the validity of the law (8.8%).
An overview of these results is given in Table 6.8.

### Table 6.8 Overview of student couple’s achievements on conceptual learning step III in their final scientific report (n=34)

<table>
<thead>
<tr>
<th>Students’ result on conceptual learning step III</th>
<th>Percentage of couples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Law is generally applicable + discussing all seven procedural steps</td>
<td>0.0%</td>
</tr>
<tr>
<td>Law is generally applicable + discussing six procedural steps</td>
<td>8.8%</td>
</tr>
<tr>
<td>Law is generally applicable + discussing one to five procedural steps</td>
<td>29.4%</td>
</tr>
<tr>
<td>Law is generally applicable + discussing no procedural steps</td>
<td>26.5%</td>
</tr>
<tr>
<td><strong>Law is generally applicable (total).</strong></td>
<td><strong>64.7%</strong></td>
</tr>
<tr>
<td>There might be exceptions + discussing at least one procedural step</td>
<td>0.0%</td>
</tr>
<tr>
<td>There might be exceptions + discussing no procedural steps</td>
<td>5.9%</td>
</tr>
<tr>
<td><strong>There might be exceptions (total).</strong></td>
<td><strong>5.9%</strong></td>
</tr>
<tr>
<td><strong>No information.</strong></td>
<td><strong>29.4%</strong></td>
</tr>
</tbody>
</table>

In an open question in the survey given to the students individually several weeks after the teaching-learning sequence the number of students that met our strict criteria for taking conceptual learning step III again was none: none of the students discussed all procedural steps. However 46.4% of the students believed the law could always be repaired when necessary and all these students gave reasons for their belief as well. Almost all of the 39.3% of students that hesitated to say that the law could always be repaired, gave as their reason that there are always exceptions in physics (14.3% of the students did not answer the question) (see Table 6.9).

### Table 6.9 Overview of students’ opinions on the general validity of the law of energy conservation

<table>
<thead>
<tr>
<th>Students’ opinion on the validity of the conservation principle</th>
<th>Percentage of students</th>
<th>Percentage of students</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Instrument</strong></td>
<td><strong>Report from assignment 6</strong></td>
</tr>
<tr>
<td>Law is generally applicable.</td>
<td>64.7%</td>
<td>46.4%</td>
</tr>
<tr>
<td>There might be exceptions.</td>
<td>5.9%</td>
<td>39.3%</td>
</tr>
<tr>
<td>No information.</td>
<td>29.4%</td>
<td>14.3%</td>
</tr>
</tbody>
</table>

Students’ opinions after a couple of weeks differed a lot from the results we took from students’ scientific reports in the final assignment. The percentages of students that dared to take a risk and state that the law is generally applicable dropped from 64.7% at the end of the teaching-learning sequence to about 46.4% several weeks later. The number of students that hesitated in taking such a risk grew from 5.9% to 39.3%.
The main issue concerning conceptual learning step III that remains to be addressed is that students do not discuss all procedural steps to formulate their answer to the general applicability of the conservation law.

6.5.4 Concept applicability

Very near transfer

We used the advice reports for each of the first three technological design assignments to assess whether the couples were able to apply the law they had derived from the assignment itself. A large percentage of couples (61.8%) realized at least for one assignment, that applying the intended law would improve their corresponding advice report. Per assignment the results were lower: 38.2%, 45.0%, and 38.9%.

The main issue left is that in several cases students did not see the need to apply the law even though they had reinvented it.

In Table 6.10 an overview is given of the very near transfer results from all schools of students applying the concept of energy conservation in their advice reports to the technological design assignments.

<table>
<thead>
<tr>
<th>Transfer</th>
<th>School 1 (%)</th>
<th>School 2 (%)</th>
<th>School 3 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very near transfer</td>
<td>61.8</td>
<td>50.0</td>
<td>80.0</td>
</tr>
</tbody>
</table>

Near transfer

The two near transfer test questions from the final test gave results of 77.2% and 64.9%. This results in an average score of 71.1% over both questions.

On the six near transfer questions in the Energy Concept Inventory our students scored comparable to Dutch exam students in their final year tested in our preliminary research (50.5% versus 52.2%). These results were higher than both high school physics students (36.3%) and university physics students (45.2%) from Swackhamer’s original tests taken in the USA.

Far transfer

The test for far transfer was also conducted during the final test. The relevant test question involving gravitational, thermal, and kinetic energy was answered conceptually correct by 26.3% of our students.

For the questions in the Energy Concept Inventory that were not identified as near transfer questions our students again scored comparable to the students from our preliminary research (38.9% versus 41.3%). These scores are between those of high school physics students (35.0%) and university physics students (44.9%) from Swackhamer’s original tests.

7 Assessed from couples’ advice reports thus classified per couple and not individually.
Overview of near and far transfer results
In Table 6.11 an overview is given of all the results on students applying the concept of energy conservation to selected near and far transfer questions in the final test.

Table 6.11 Overview of the results on students’ application of the energy conservation law in the final test

<table>
<thead>
<tr>
<th>Transfer</th>
<th>Total (%)</th>
<th>School 1 (%)</th>
<th>School 2 (%)</th>
<th>School 3 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near transfer</td>
<td>71.1</td>
<td>33.3</td>
<td>86.5</td>
<td>64.0</td>
</tr>
<tr>
<td>Far transfer</td>
<td>26.3</td>
<td>0.0</td>
<td>38.5</td>
<td>20.0</td>
</tr>
</tbody>
</table>

In Table 6.12 an overview is given of all the results on students applying the concept of energy conservation to selected near and far transfer questions in the Energy Concept Inventory.

Table 6.12 Overview of the results on students’ application of the energy conservation law in the ECI

<table>
<thead>
<tr>
<th>Transfer</th>
<th>Total (%)</th>
<th>School 1 (%)</th>
<th>School 2 (%)</th>
<th>School 3 (%)</th>
<th>Dutch exam students(^8) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near transfer</td>
<td>50.5</td>
<td>55.6</td>
<td>50.0</td>
<td>49.1</td>
<td>52.2</td>
</tr>
<tr>
<td>Far transfer</td>
<td>38.9</td>
<td>40.8</td>
<td>33.7</td>
<td>40.8</td>
<td>41.3</td>
</tr>
<tr>
<td>Overall score</td>
<td>40.9</td>
<td>43.3</td>
<td>36.5</td>
<td>42.2</td>
<td>43.2</td>
</tr>
</tbody>
</table>

6.6 Conclusions

1. The percentage of couples of students that were able to generalize experiences into partial conservation laws (conceptual learning step I) was 64.7%.
   This step has been tested most extensively so in future try-outs we do not expect much improvement in comparable contextual settings as ours. Variations between classes were observed between 46.2% and 83.3%. In the class with the lower number another 46.2% of the couples (i.e. 17.6% of the total number of couples) did not show a complete derivation which partly may have been caused by being given the subsequent worksheet containing the resulting partial law before the students had finished the worksheet in which they had to derive that law. Had this been done correctly we might have seen comparable results to the other classes in which 73.3% and 83.3% managed to take conceptual learning step I.

2. Combining partial laws (conceptual learning step II) has only been tested twice and now showed an achievement rate of 32.4% during assignment 6.

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\(^8\) Calculated from preliminary research results (Borsboom et al., 2008).
In the individual test only a small percentage of students (5.3%) were able to memorize the necessary steps for the final test.

During this try-out several issues have been found. To improve the results in a future try-out we recommend to clearly separate conceptual learning step I from step II and make it clearer to the students how the domain of the law changes during the combination process (Logman et al., submitted-b). This way, experiencing the benefits of a combined law may clarify the combination process for the students and improve their results.

One of the schools albeit with only a small number of students showed a rate of 66.7% during assignment 6 so possibly similar achievement results as for conceptual learning step I may be reached once these improvements are implemented.

3. None of our students met our strict requirement of critically discussing all procedural steps for combining partial laws.

Generalizing the combination process (conceptual learning step III) has only been tried out once. We have seen only a few students discussing six out of the seven procedural steps towards taking the full conceptual learning step (8.8%). About a third of the couples saw the need for discussing these procedural steps in solving the final scientific assignment and discussed at least one procedural step (38.2% in total: 8.8% discussed six steps and 29.4% discussed one to five steps). In the survey several weeks later the number of students with an opinion on the validity of the law grew from 70.6% (64.7% pro and 5.9% hesitating) to 85.7% (46.4% pro and 39.3% hesitating) mostly due to students giving reasons why the law might not be valid (see Table 6.9). Both types of students are ready to enter a scientific discourse on the validity of the general law of energy conservation. This is not the case in education in which the law is stated as an indisputable fact.

It is recommended to build further upon this capability in a future design and organize a classroom discussion in which the general validity of the law can be discussed. This way the students can be guided by the teacher to discuss the procedure more extensively. Because at that stage most of the students are convinced that the conservation law is generally valid the teacher may have to bring arguments against the general validity into such a discussion.

4. Our students, one or two years before the final exam, scored similar results on the Energy Concept Inventory as Dutch exam students did in preliminary research (40.9% versus 43.2%).

During the one or two years that our students will still be in secondary education the concept of energy will be addressed several times. Therefore we expect better results when the final exam arrives.

For very near transfer our results show that 61.8% of the students apply their newly reinvented law in their advice report. Per assignment these results lie around 40% so more than one assignment is necessary for students to see the need for applying a physical law to solve a technological design problem.
Test questions on situations from within investigated domain parts (near transfer) show an average success rate of 71.1%. On a test question from a domain part in which three forms of energy play a role (far transfer) the students score much lower (26.3%). If we divide the Energy Concept Inventory questions into similar near and far transfer domains we see that the results again are comparable to results for Dutch exam students taken from preliminary research.

### 6.7 Discussion

To see if our teaching-learning sequence is socially acceptable we compare it to the exam requirements given by the Dutch innovation committee for physics (Groenen et al., 2012; van Weert et al., 2012). Exam requirements A12 and A15 on mathematical skills (see Appendix A) are covered mostly by conceptual learning step I so students that took that step are considered to have covered these exam requirements as well. These skills are normally not addressed in traditional teaching on the subject of energy. Both conceptual learning steps II and III ask more from the students than what is asked by the exam requirements.

Exam questions covering exam requirement C2 (amongst others applying the concept of energy conservation) cover the same domains as the near transfer questions and are therefore comparable to them. Most Dutch exam questions on energy however concern energy efficiency, power, and intensity next to energy conservation but in our teaching-learning sequence we address energy conservation only. More work on this exam requirement therefore needs to be done after our teaching-learning sequence during the one or two remaining years.

Exam requirements that focus on competencies and skills like technological design, experimenting, and scientific communication are addressed in our teaching-learning sequence as well but we refer to another article for an analysis of this aspect (Logman et al., submitted-b).

Considering the above we think that our teaching-learning sequence matches the new context-based Dutch exam program better than the traditional approach.

### References


