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ABSTRACT

This study investigates the difficulties first year chemistry students have with learning the concept of energy. Students have difficulty understanding heat and work as path functions and energy as a state function. Textbooks analysis, the evaluation of current practice and teaching experiments, and epistemological analysis were conducted during the study, and all are reported on. (YDS)

Teaching Energy without Dogma

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Teaching Energy without Dogma

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1. Introduction

In secondary education, energy is usually taught starting from a statement that different *forms* of energy *exist* and that these forms can be *converted* into each other. Visible phenomena are presented as indications of such conversions. In this paper we will question this starting point.

The objective of our study is to find explanations and remedies for the difficulties that first year chemistry students (at the university of Amsterdam) have, when learning the subject of energy as a ëfunction of stateí. Remedies to these difficulties were tried in two educational experiments, which were linked to the standard thermodynamics course at our faculty. Part of the objective was to formulate recommendations for teaching at secondary level in order to alleviate the difficulties experienced.

Studentsí difficulties with understanding heat and work as ëpath functionsí in contrast to energy as a ëstate functioní, have been reported before. It has even been suggested that path functions, like heat and work, should be eliminated from thermodynamics. Other authors have stressed that these concepts can be given clear meanings, with or without changing their names as Bent has proposed. No attempt has been found to understand university studentsí difficulties with ëpathí and ëstate functionsí as a result of secondary school teaching. Remedies suggested therefore do not sufficiently take students background into account. To do this is the objective of the present paper.

2. Perspective on teaching and learning

Our research program aims at describing learning processes as changes of language. By ëlanguageí we mean a system of signs that refer to experiences. A ëlanguageí can be described by noting for each sign the class of situations (experiences) to which language users apply that sign *and* by noting the non-accidental relations (co-occurrences) between signs. Such a description would include a description of general statements like ëenergy is conservedí because these are non-accidental, repeatedly used, relations between signs. The description of a language thus contains a description of beliefs held to be generally true, or you may say it implies a worldview. Therefore, what we call a language may be given other names, for instance: frame of reference, conceptual system, or the like. Essential to this way of analysis is that we think it not useful to separate beliefs from the sign-system in which they are expressed. From this premise it follows that a learning process can be described as a process of change of language-in-use.

3. Procedure

The procedure of this study is given schematically in Table 1.

1) A researcher, working at the Research group of Chemical Education, participated as a teacher in the thermodynamics course for first year chemistry students at our faculty. The course consisted of lectures and tutorial sessions. Tutorial sessions were done in smaller groups and they were taught by junior (mostly physical) chemists, among which the researcher was one. Purpose of this participation was twofold: evaluation of current practice "from inside" and preparation for three teaching experiments in following years. All lectures and tutorial sessions were tape-recorded and studentsí answers to the end-of-course exam questions were available for analysis.

Table 1: procedure

1. Description of problems in current teaching practice,
   - from tape recordings of teacher-student dialogue
   - from end-of-course exam
2. Interpretation of problems found, in the light of students history in secondary education. Developing interpretations into plans for remedies.
3. Testing and further development of interpretations / remedies in three subsequent teaching experiments.
   - teaching (in small groups)
   - tape recordings of student-student and teacher-student dialogue
   - interpretation of teaching problems (back to step 2)

First, tape recordings were analyzed by identifying longer-lasting dialogues between teacher and a student in which no satisfactory outcome emerged. These dialogues were classified according to the concept that seemed to cause the problem. Answers on the final exam were used to check quantitatively the importance of the problems found.

2) Next, it was attempted to explain studentsí difficulties from their learning history. To this end, texts used in secondary schools were analyzed and a comparison was made between these books and the text that was used in our course. Tentative interpretations of teaching problems were developed into remedies. Interpretation and remedy together constitute a hypothesis to be evaluated.

3) In subsequent years, two teaching experiments were performed in order to evaluate our hypotheses. The experiments were performed with very small numbers of participants (varying between 5 and 8). Volunteers were requested. Students participating received their tutorial sessions in two small groups of 2-4 students, which were taught by the researcher. This was done in order to have a close look at what happened during the experiment, and to have intensive interaction, in order to gain detailed experience with the proposed teaching setup. All sessions were tape-recorded.

Tape recordings of student-student or student-teacher discourse were analyzed in various ways, of which only one will be treated in this paper: we will show an ëepistemologicalí analysis that we used. Terms used in teaching and learning were divided into *model terms* on the one hand, *observables* on the other. We used the following characteristics in order to distinguish these:

Tabel 2: distinguishing model terms from observables

observable terms	model terms
confident, factual use	tentative use
meaning unproblematic	meaning subject to evaluation and change
consensus on applicability in different situations	subject of discussion or debate
used for formulating ëexperiencesí	used for explanation or prediction of observable terms

Note that our proposed definitions do not prohibit todays ëmodel termsí in becoming observables tomorrow. In other words, we do not consider ëexperienceí as something that can be separated from conceptual development in any absolute way (like the empiricist philosophers wanted to do).

Texts from secondary schools as well as our own text were analyzed with respect to whether the text showed or promoted awareness of this distinction. Results were used to explain a certain difficulty that we had encountered unexpectedly. This tentative post-hoc explanation was then tested by revising our teaching sequence according to our new understanding and checking whether a more fruitful learning occurred.

Because of the small number of participants, analyses of the teaching experiments never concerned the quantitative aspect of a certain type of answer or discussions. It only concerned the rationality of students and teachers reasoning, interpreted in the light of their separate and common history.

1. Results

i. Evaluation of current practice

Our evaluation of current practice revealed the following problems. The concept of ëstate functioní was not used by most students in their reasoning. Questions on *energy* were answered using the ëlaw of energy conservationí but 77% of students (n=65) did not use ëstate functioní when necessary in their reasoning. A one-hour lecture about *entropy* being a state function had had unsatisfactory result, as the concept of ëstate functioní was absent in 69% of answers on a relevant exam question. This resulted in 46% wrong answers (a non-zero entropy change for a cyclic process) and to 23% lack of answer.

Second, tape recordings showed that the distinction between process-functions and state functions was not understood by students. Students (from two independent groups) did not understand the teacher when he wanted to attribute ëheatí to a process at constant temperature, for instance the melting of ice or the compression of a gas at constant temperature. Other students protested heavily when a teacher wanted to attribute zero heat to a process in which a temperature change occurred. From these data, it may be concluded that our student population sees temperature as *the* variable that determines heat. In thermodynamic language, this suggests they use heat as a state function. This interpretation is confirmed by students use of ëΔ qí, in spite of explanations why this notation is not applicable.

ii. Textbook analysis

The teaching problems mentioned were explained using knowledge of the learning history that our students have in common. This knowledge was obtained from an analysis of textbooks used in Dutch secondary schools......, compared to the text used in our course.

In secondary education, energy is usually taught starting from a statement that different *forms* of energy *exist* . Observable and changeable properties of objects are used to attribute ëenergyí to objects. This ëenergyí is classified according to the changeable property involved. Thus kinetic energy is determined by an objectís speed, gravitational potential energy by its height, heat by its temperature, elastic energy by its length and chemical energy by its composition. Apart from *one* (and only one) changeable property, only constants are involved in calculating the amount of energy *of a certain form* in an object. When two properties change simultaneously for one object, this is reason for saying that one form of energy has been *converted* into another. When one property changes simultaneously for two objects, this is reason for saying that energy of a certain form has been *transferred* .

In thermodynamics textbooks.. the expression ëforms of energyí is scarcely used. If this is done, it is in connection to heat or work. Expressions like elastic energy, chemical energy, electrical energy do not occur in thermodynamics texts, although elastic, electrical and chemical phenomena may be treated extensively! When heat and work are called ëforms of energyí then this expression is used with a meaning different from the one intended in secondary school. In thermodynamics, heat and work certainly do not *exist* in objects, but rather, they happen (work is *performed*). The expression ëforms of energyí therefore does not refer anymore to separate portions into which the total energy might be subdivided. Instead the ëinternal energyí of an object is treated as *one* quantity that depends on *many* variables. Its change is subdivided according to the kind of interaction that allows transfer of energy.

Both kinds of textbooks (university-level and secondary school) show no sign of being aware of the others existence. Thermodynamics texts do not start from ëforms of energyí as taught in secondary schools, but rather they start from their own definitions of work, heat and internal energy. Texts for secondary schools do not show any awareness that the truths they tell are partial or temporary truths.

iii. Evaluation of first teaching experiment

Our first teaching experiment consisted of a series of assignments, ending with an assignment designed to let students experience a difference, between a state function and a path function. Results of measurements were presented that allowed students to calculate what they call the ëchange in chemical energyí and the ëchange in heatí (their terms), for two different processes. Both processes started with a mixture of hydrogen and oxygen at 125 ^{o}C and pressure p_1 and both ended with water vapor at 325 ^{o} C and pressure p_2.

Students were much surprised that they could attribute neither one unique ëchemical energyí nor one ëheatí to the final state(s) of both processes. However, they did not conclude from their findings (which they accepted) that the something they named ëheatí was a path function, as we hoped they would. Instead, one student argued forcefully that both processes did not end in the same state, because they had just found out by measurement that different amounts of heat were present in the final states of both processes. Therefore, the assignment incorrectly talked about ëoneí state.

Although only one student presented this argument, all students were amazed and we felt they were not ready to understand their findings. Moreover, we thought afterwards that the student who protested was right from his point of view. *If* you consider heat or chemical energy as equally concrete and measurable as temperature and pressure, then you have no reason to abandon the view that heat exists inside of objects. Instead, you can just as well add ëheatí to the list of independent state variables! We concluded that the ëforms of energyí model can be described as resistant to change, and that we did not have an adequate answer yet to this resistance.

iv. Epistemological analysis

The previous result can be analyzed in what one might call an epistemological way. Textbooks from secondary schools are included in this analysis. We start by noting that the student has ëa modelí of the universe that differs from ours. In his model, certain entities that we consider not observable do exist. Their expressions ëheatí and ëchemical energyí refer to such entities. We can not reach consensus with them on the use of these terms, therefore they are not ëobservable termsí in the group of students plus teacher However, students can use these terms for making predictions, for instance, they can use their term ëheatí in order to predict the final temperature of a portion of water, after a hot object of a known metal has been added to it. ëTemperatureí is a term that students and teacher had no difficulty agreeing about, it is therefore best described as an observable term for this group. Their term ëheatí, because it can be used by students to make predictions on temperature, can now correctly be identified as a model term in this same group.

In science, models are tested (Popper) or they compete with rival models (Lakatos). In short, models are evaluated by the science community with respect to their ability to order experiences described with observables.

In order to enable such an evaluation, participants themselves must make a difference between terms that belong to the model to be evaluated on the one hand, and observable terms on the other. If all terms would be considered equally observable or equally hypothetical, then after an unpredicted outcome of an experiment it can not be decided which of all terms used has to be abandoned. ëTemperatureí can be blamed equally well as ëheatí. The model, therefore, must be experienced as *having a function* , namely: predicting terms that are considered more concrete, more readily agreed-on than the model terms itself.

If students in our first teaching experiment had made a distinction between model terms (like their ëheatí) and observables (like temperature), their decision to distinguish two states on account of different amounts of ëheatí could have been questioned. Their teacher could have asked them why they chose to complicate their model by distinguishing states that, by all observable measures, are the same. However, students did not make this distinction and therefore the teacher stood with empty hands.

Now we can explain the outcome of this teaching in the light of studentsí learning history. In secondary schools, ëforms of energyí are not taught as model terms. No distinction in status is made between terms (like temperature) that are to be predicted and terms (like heat) that are tools for prediction and can be evaluated. Also we ourselves had not made this distinction in our teaching! That is why the discussion had ended unsatisfactory to both parties: we had not yet analysed ëforms of energyí as a model term.

v. New teaching setup

The following citation from Ernst Mach contains a clue to analyze ëenergyí as a tool for explanation or prediction:

Only experience can show that a fall from height h creates a velocity v, that using this velocity the original height h can be reached again and that quantitatively $v = \sqrt{2g}$ This however, does not yet imply an equivalence, because for a long time people have used this equation without thinking of an equivalence. When I start saying, however, that this v for me has an equal value as this h that it is able to conquer, then this is a way of interpretation (Ger. "Form der Auffassung") that can satisfy my needs.

Note that Mach's expression "Form der Auffassung" denotes what we called a model; it serves to order experiences with observables like h and v. Note also that Mach is not against choosing a "Form der Auffassung", he does *not* say that science should stick to observables.

Our experimental teaching setup was revised in the following way, in order to enable students to experience ëenergyí as well as ëforms of energyí as terms in a model. We start by asking students to use ëforms of energyí in a few situations they already studied in secondary education, like throwing a stone upward with given velocity or mixing two quantities of water with different temperatures. Next, we ask whether ëenergyí may be interpreted as ëthe exchange value of a phenomenoní and if this is agreed, we ask students to explain their meaning of ëexchange valueí.

Then the question is asked whether ëexchange valuesí could be calculated in other ways. For instance, given a stone thrown upward and asked the maximum height, the prediction can also be made with gh (instead of mgh) as the exchange value for height and with ‡ v^2 for velocity. These assignments were meant to give students a feel for ëenergyí as a tool, which can be evaluated and compared to possible alternatives.

The sequence continued with the introduction of a "heat capacity" that depends on its own associated variable, the temperature. It was intended that students experience a need for the calculus of integration, before introducing this calculus in the course. The teaching sequence ended with the same assignment described previously (section iii), about comparing changes in ëchemical energyí and changes in ëheatí for two different paths between the same initial and final states.

vi. Evaluation of final teaching experiment

First, we mention the result of the final assignment, the one that previously had failed to convince students of the distinction between state- and path functions (section iii). Thereafter we will relate this result to the change we made in earlier parts of the assignment sequence (section v).

The final assignment (described in section iii), about comparing two paths between "the same" initial and final states was discussed very differently by this new group of students. Students concluded in a matter-of-fact way that the concepts they called ëheatí and ëchemical energyí were path functions, not state functions. After adding the two path functions involved, they concluded that the total energy of the system was a state function. Students were not surprised by their conclusion that chemical energy and heat were path functions.

In order to understand this result, we will now report the discussions that concerned our introduction of ëexchange valueí (see section v). This expression was introduced in the course of the following assignment:

A 10-kg stone is falling straight downward, 4 meters through the air.

a. Which form of energy decreases in this process? Which form(s) of energy do(es) increase?

b. If the stone is falling through a vacuum, can you use these forms of energy to calculate the velocity at which the stone will touch the ground? If yes, show it.

c. Consider the general *proportion* between the height lost, Δ h, and the velocity-squared, v^2, gained by this stone. Derive this proportion from the proportion between the form of energy that decreases and the one that increases.

d. Which change in velocity squared would you call equivalent to a change in height of 1 meter?

e. Which change in height would you call equivalent to a change in velocity-squared of 1 m^2/s^2?

f. A 10-kg stone is thrown upward in vacuum at an initial velocity of 2 m/s. Use your answer from (e) to predict its maximum height.

g. Which experiences can be our reason for calling the two phenomena mentioned in (e) ëof equal valueí (equivalent)?

h. In the introduction to this section, we promised that ëenergyí could be interpreted as ëthe exchange value of a phenomenoní. Do you agree with this? If yes, what do you mean by ëexchange valueí?

The name ëexchange valueí was accepted by students after discussion, as a possible interpretation of ëenergyí. Talking about question **h**, one student (P) explained ëexchange valueí to his partners by working out a comparison between energy and money. The following transcript shows this discussion.

O Shit, so you have these two (Δh and Δv^2), yes, can you call these ëphenomenaí?

N Exchange value seems to me something likeÖ converting one into the other, by way of the exchange value or multiplied by the exchange value, like that, thatís how I understand it.

P Yes, but exchange value..? You convert velocity into height, and then again height into velocity. But thereís nothing intermediateÖ? ThereísÖ Oh, yes! So, so maybe you could look at energy like you regard money, withÖ just like a unit.

O Like this: you have a piece of matter. Thereís a certain energy in it. And thenÖ thereís an other energy here somewhere.

P Yes

O and then those two are going to exchange with each other

P yes, soÖ

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O So this piece of matter suddenly gets another energy

P The exchange value, so theÖ (silence), the value that you use to do the calculation. You can, so, the velocity and the mass you can convert into this one energy. And the height and the mass you can convert into potential energy: both energy! En then you can compare them. And thatís what itís about.

O Are v^2 and m potential energy now?

P You can, if youÖ important isÖ eh... v^2 and h, thatís what we are talking about, is it?

O yes

P Well, you can, ehÖ v^2, eh.. m can be left out because thereís no friction. v^2 you can convert into energy, you can recalculate it as energy. Therefore energy is theÖ something you calculate in.

O They are two forms of energy

P yes

O Itís not one, velocity.

P NóÖ of course not, but you can compare these to each other. You can say, ehm... about the velocityÖ if you throw it upward like this, at the dead point the energy has been converted into that other energy. So there you have to...

O Well, I find the wording still unclear.

An exchange valueÖ and whatís a phenomenon then? (silence) Do you regard energy like something ehÖ So: potential energy and kinetic energy the same? And ehÖ those are transferred to: it starts with this v^2, this v^2 then has this energy, and then it ehÖ then itís not the energy that gets exchanged, but the h gets there in place of the v.

P yes

O So itís not the energy that exchanges, but the phenomenon, so, the v^2 and the h do exchange.

P Yes, thatís because itís another kind of energyÖ ButÖ you can look at it just like an ehÖ just a valueÖ just like, an object also has a value, in money or something like that. And then you can convert it into another object.

N By way of the money!

P It hasÖ By way of the money! Yes, that makes a difference, you mean.

O Then you have therefore always only one and the same energy!

P Yes, but then energy is always, is always in Joule? Only, this energy is called differently because it has different causes, different origin.

The comparison initiated by **P** between energy and money can be summarized as follows. Objects can be exchanged if they have the same value in money. In a comparable way, a certain height and a certain velocity can be exchanged if they have the same energy value. Energy values make different phenomena comparable by expressing them in a common unit. The purpose of this is to decide whether those phenomena (a height and a velocity) can be exchanged. During this discussion, **O** notes with surprise, "then you have therefore always only one and the same energy!" His surprise concerns his recognition that the energy concept proposed by **P** can be functional without assuming the separate existence of ëforms of energyí.

We are now in a position to understand the lack of surprise when students concluded, at a later stage in their learning, that their terms ëheatí and ëchemical energyí referred to path functions. This lack of surprise can be understood if we realize that in this case, the surprise had come earlier, namely at the moment when **O** exclaimed: "then you have therefore always only one and the same energy!" Note also that this time the character of the surprise had been different. It had not been a surprise about unexpected findings, but instead a surprise about the possibility of choosing a new point of view (Machís "Form der Auffassung"). The distinction between state- and pathfunctions could be recognized as useful, now that a purpose and use for the energy concept itself had been explicitly formulated by the students.

2. Conclusion

In secondary education energy is usually taught starting from a statement that different *forms* of energy exist that can be converted into each other. In this article, we have questioned this starting point. We have shown that these ëforms of energyí render the understanding of internal energy as a state function more difficult than is necessary. In particular we have shown the following:

- The forms of energy concept learned in high school is resistant to change, because of a premature emphasis on energy as something that *exists* (as a fact), instead of on energy as a model term, a term that performs a function in the prediction of observables.
- Model terms should remain open for evaluation and development. Such a development is impeded if learners do not distinguish between model terms and observables.
- A change from ëforms of energyí towards ëinternal energyí becomes possible when students have analysed the ëforms of energyí concept in relation to experiences, that is: when it becomes a model term *for students*.
- A concept named ëexchange valueí proves to be valuable in this analysis. It can also serve to eliminate and replace ëforms of energyí as an intermediary on the road to ëinternal energyí.

These conclusions are the result of an ëepistemologicalí analysis of student- and teacher reasoning, in relation to texts that they have worked with. This epistemological analysis concerned itself only with the structure and reasonableness of student- and teacher reasoning, not with the frequency of student- or teacher ideas. However, some quantitative results were used to demonstrate the importance of the problems discussed.

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