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Learning chemical thermodynamics at school: the use of non-interactive views to interpret energy changes

A. F. Cachapuz and I. P. Martins
University of Aveiro - Aveiro, Portugal

I - Introduction

An important message of science education research in the last decade is that a major requirement of successful science teaching involves the appreciation of pupils' alternative ideas about science concepts (Helm and Novak 1983: Novak 1987; C.N.R.S. 1984). Evidence from these studies strongly suggest that pupils' alternative ideas may arise before and during instruction. Also they are usually resistant tó alternative instruction (Nussbaum and Novick 1981).

In the domain of the energy of chemical reactions recent results (Cachapuz and Martins 1987) suggest that Portuguese high school students may use sequence models to explain the process of energy changes in chemical systems (NH_4Cl/H_2O). For example, students may use a serialistic reasoning not involving the coordination between the energetic components associated with the bond -breaking and bond-making processes. These processes would take place one after the other instead of being simultaneous and thus, for these students, the key notion of a net energy balance was probably not appreciated. The authors pointed out that the use of sequence models is consistent with a limited capacity memory model (Johnstone 1980) as the "... understanding of energy changes associated with a chemical reaction implies a holistic perception of the reacting system involving the coordination within and between two sub-systems, hence a high level of information. Use of a sequence model may be a way to lower memory overload" (Cachapuz and Martins 1987, p.66). Sequential ways of reasoning have also been reported in other subjects of the school science curriculum, in particular in the area of electric circuits (an upstream and a downstream without effect on the upstream) (Shipstone 1984; Dupin and Johsua 1987).

In this study we further investigate the use of sequence models by Portuguese pupils to explain energy changes in the case of combustions, a very important type of reaction studied at various stages of the Portuguese secondary chemistry curriculum.

In Portugal, the topic of chemical reactions is formally introduced in grade 8 (age

14). At this level (and also in grade 9) the idea of chemical change is simply equated in terms of the separation/reorganization of atoms with no mention of the nature of the chemical bonds involved (this latter notion is only elaborated in grade 10). Notions of exothermic/endothermic processes are introduced in the usual manner (heat given out/ heat taken in). Thus in a combustion, the reaction gives out heat to the surroundings because the products have less energy than the reactants. In grade 11 (age 17) the above aspects are refined and energy changes are now explained in terms of a formal model involving the ideas of bond breaking/bond forming and associated enthalpy changes. At this stage students become familiar with the notion of internal energy and are expected to use structural models to understand the notion of a net energy balance. Thus, in a combustion, the energy required to break the bonds is lesser than the energy given out by the making of bonds. Reaction mechanisms and the posible existence of reaction intermediates is only developed at university level.

The example of combustion chosen was the combustion of paper, a familiar, safe and cheap experiment which can be easily carried out at individual level in a chemistry class. The study aimed:

(i) To investigate students' representations of the energy changes associated with the combustion of paper, in particular the use of sequential models.

(ii)To analyse whether earlier ideas used to explain energy changes resist instruction.

(iii) To make proposals to teachers and curriculum developers on which to build useful alternative teaching methods.

II - Method

Data gathering involved two interrelated steps:

(i) An exploratory step consisting of in-depth individual interviews of 15 Portuguese students from grade 9 and 14 from grade 11. The interviews (no time limit was set) were based on an experimental task consisting in the combustion of a small piece of paper placed over a glass plate and burned with the help of a match. Typical questions used were: "What happens to the ... (reactant)?"; "Why is heat felt in the surroundings?"; "Where does the energy come from?". Content analysis of the interviews written protocols closely followed the method proposed by Erickson (1979).

(ii) A developmental step aiming at a more general empirical check of the results of the previous step and involving the administration of a short pencil-and-paper test (Figure 1). Items of the test were constructed on the basis of insights obtained in step one. Students were called upon to give their opinion on statements concerning ideas about energetic aspects of the same reaction. All the items were false (T responses) as no student in the first step gave the acceptable answer, previously defined by their teachers. The test was administered by the chemistry teacher during a normal chemistry class and it was anonymous. Slight changes were introduced in the final instrument as a result of a pilot study (N = 30). The final sample (N = 448) was formed by 262 students from grade 9 and 186 from grade 11. As in the exploratory step pupils were drawn from mixed ability classes of schools located in urban areas of Portugal.

Figure 1. Test used in the developmental step.

When combustion of a piece of paper occurs in contact with the air, ignited by the flame of a match, ashes are formed and smoke is released into the atmosphere; during combustion heat is felt in the surroundings.

Please indicate (in the space provided) which of the following statements are true (T), false (F) or don't know (DK). If you consider that all the alternatives are false, please write your suggestion in "Other".

A) During the reaction, first energy is released (E_1) when bonds are broken in the oxygen and in the paper; then there is energy absorption (E_2) to form news bonds in the products of the reaction. As E_1 is greater than E_2, heat is felt in the surroundings........ ☐

B) Paper combustion is a reaction which is partially endothermic and partially exothermic because energy had to be given to the paper (by the match) and then that energy was released in the form of the heat which is felt in the surroundings........ ☐

C) During the reaction, first energy absorption takes place (E_1) to break the bonds in the oxygen and in the paper; then there is energy released (E_2) when new bonds are formed in the products of the reaction. As E_2 is greater than E_1 heat is felt in the surroundings........ ☐

D) The flame which can be seen on the burning paper is the flame from the match which was used and which passed on to the paper when it was ignited... ☐

Other ____

____

III - Results

Data obtained in the developmental step for both grade levels is presented in Table 1.

Table 1. Percentage of true (T) and don't know (DK) responses.

Item	grade 9 (N = 262) (T)	grade 9 (N = 262) (DK)	grade 11 (N = 186) (T)	grade 11 (N = 186) (DK)	average $\overline{X}$ (N = 448) (T)	average $\overline{X}$ (N = 448) (DK)
A	35.8	32.5	24.6	14.7	31.2	25.1
B	76.3	9.2	68.9	6.0	73.2	7.9
C	34.7	31.3	59.6	16.4	45.0	25.1
D	61.8	9.2	38.3	7.1	52.0	8.3

The results suggest three main problem areas:

(i) the use of sequential models to interpret energy changes associated with the combustion of paper (items A and C);

(ii) the lack of differentiation between the concepts of endothermic and exothermic reactions (item B);

(iii) local ways of reasoning to interpret the production of the flame during the combustion (item D).

(i) <u>Sequential models</u>

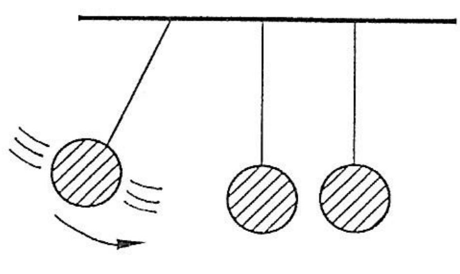
There were two types of sequential models. In both cases students represented bond-breaking and bond-forming processes in a serialistic way, i.e. not taking place simultaneously. Also, they probably considered that the energy of activation (Ea) was absorbed by the chemical system becoming involved in the structural process itself.

In the first model, subtractive model (item C, $\overline{x} = 45.0\%$), energy changes during the combustion were described as follows. First, the system absorbs the energy coming from the match (Ea) and as a result bond-breaking (in the paper and oxygen) took place. Bond-breaking was perceived as an endothermic process. Then, new bonds were formed in the products, an exothermic process (E_1), with $E_1 > Ea$. Afterwards the energy excess $\Delta E = E_1 - Ea$ played the role of an "activation energy" and the whole process started again so that a new portion of paper was burned. At the end of this iterative process the last ΔE term was responsible for the heat felt in the surroundings. For example (quotation from the interview): "...when we give energy (match), the atoms of the oxygen and of the paper break apart... then they are linked up in a different way and give out more energy than the energy they received... the energy given out when the first atoms break apart is used to help other atoms to be separated" (grade 11).

Despite its mechanistic connotations, this model involved a structural appreciation of energy changes in a chemical system. This may explain its dominance among grade 11 students and the high percentage of DK responses among grade 9 students in the developmental step.

The model seems to be quite resistant to formal instruction (over half of grade 11 subjects) possibly because of its plausibility. In fact it may be consistently used to interpret everyday experiences the students are confronted with. For example, the model isn't necessarily contingent upon the nature or the amount of combustible material involved. Thus, wood fires (high E_1) ignited by a single match may be easily explained: $E_1 >> Ea$, thus a high ΔE; this is consistent with a large amount of heat usually felt in the surroundings. On the contrary the model doesn't explain why heat was evolved from the beginning of the reaction.

In the absence of an appropriate model of energy changes it is possible that these students may have used models transferred from mechanistic contexts. For example, experiences with balls such as



involving a serial interaction. Also, instructional models such as diagrams of the potential energy as a function of the reaction coordinate may reinforce non-interactive models of the chemical process, as products and reactants are represented as physically separate entities.

The second type of sequential model, additive model (item A, $\overline{x} = 31.2\%$) was formally identical to the one previously described. In this case, however, students considered bond-breaking as an exothermic process and bond-forming as an endothermic process. Students think that the energy given out (E_1) was added to Ea since the beginning of the combustion; then, part of the (E_1 + Ea) term was used again in bond-forming (an "activation energy" component necessary to iterate the process) and the remaining amount of energy was evolved to the surroundings. For example (interview transcript): "...when energy is given (match) there is bond breaking and the energy given out is added to the first... it's always like that... when the bonds are broken I think energy is evolved and when bonds are formed it absorbs energy and the result of these two terms is what explains the surplus energy which was felt..." (grade 11).

This model strongly involved a materialistic view of energy, as an entity which was kept in the bonds and then released, somewhat like a compressed spring within a box when the cover is opened.

Again a substantial number of grade 9 students didn't know how to answer. Compared with the first model this one was less consistent with the accepted instructional model (grade 11). This probably explains the shift observed for students from the upper secondary classes (Table 1).

(ii) Exothermic and endothermic reactions

It is clear from results of item B ($\overline{x} = 73.2\%$) that most students were not able to differentiate between endothermic and exothermic processes. Clearly in this case immediate experience rather than theory guided students' responses. Thus, they probably think that non-spontaneous reactions must be always endoenergetic. In our view, at the heart of this difficulty is the failure to appreciate the notion of an energy barrier in chemical process (activation energy). These students probably thought that Ea was directly related with the thermodynamic energies, an aspect involved in the additive and subtractive models referred to in items A and C (overlap index: $i_{B,A} = 0.703$ and $i_{B,C} = 0.840$). (Overlap index, $i = \dfrac{\Sigma T}{\Sigma T + \Sigma F}$, ΣT = number of T responses in both items;

ΣF = number of F responses in the same two items). Without a qualitative notion of Ea (only in grade 11), students may find it difficult to appreciate why once the combustion starts the source of energy may be removed without stopping the reaction, contrary to, say, the decomposition of $CaCO_3$.

(iii) Local ways of reasoning

Responses to item D ($\bar{x}$ = 52.0%) suggest that a substantial number of subjects (mainly from grade 9) used surface descriptions to explain the production of a flame during the chemical process. The flame was not perceivedas a result of the reaction itself; rather it was thought that it was the flame of the match which was transferred to the paper. For example: "... that flame we see on the paper is the match flame which was transferred from the match to the paper..." (interview).

The lack of chemical knowledge about the combustion of the paper (a complex chemical system) does not probably explain all the difficulties underlying the use of such a local model. In our view usual procedures used in the classroom to initiate a combustion may influence the conception identified. In fact, these reactions are usually ignited with the help of a match, Bunsen burner,... Thus, at the phenomenological level there is an overlap between features (flame) of the initiating agent and equal features of the reaction itself. To overcome such a possible confusion it may be of help to initiate the combustion of the paper using a lens or an electrical filament heater.

IV- Implications for teachers

Energy changes in chemical systems is a difficult concept to master. The results of this investigation indicate a widespread use of sequential models to interpret energy changes associated to an important type of chemical reactions (combustions). Students failed to consider the chemical reaction as a system. They seem to have represented the chemical process in terms of successive steps taking place in a sequential way.

The results further suggest that students were not able to discriminate between the concepts of endothermic and exothermic reactions. They seem nevertheless to have conceptualized energy as an extensive property. Steps should be taken to introduce, in a qualitative way, the notion of an energy barrier in chemical systems in grade 11. Otherwise, aspects which are vital to our lives, e.g. why fuels do not spontaneously burn on contact with air, will remain a mystery.

The role of instruction seems to have been a limited one as earlier inadequate conceptions resisted to a greater or lesser extent from grade 9 to grade 11. This was probably because students were successfully using inadequate models to make sense of some of their ordinary experiences. As a result these models were probably psychologically satisfactory.

The understanding brought about by this research should help teachers to be cautious with some of the common procedures used when dealing with the subject of combustions. For example, the nature of the initiating agent should be more varied. Also, language should be carefully scrutinized as it may reinforce the idea of activation energy being absorbed by the system (Ea is often said to be "given" to it to start the reaction). Empirical validation of these aspects is now under way.

This report was mainly descriptive in character. Also, it included both qualitative and quantitative data. This was intended to have a greater impact on teachers as the ultimate aim of this research is to provide them with insights on which useful alternative teaching strategies may be based.

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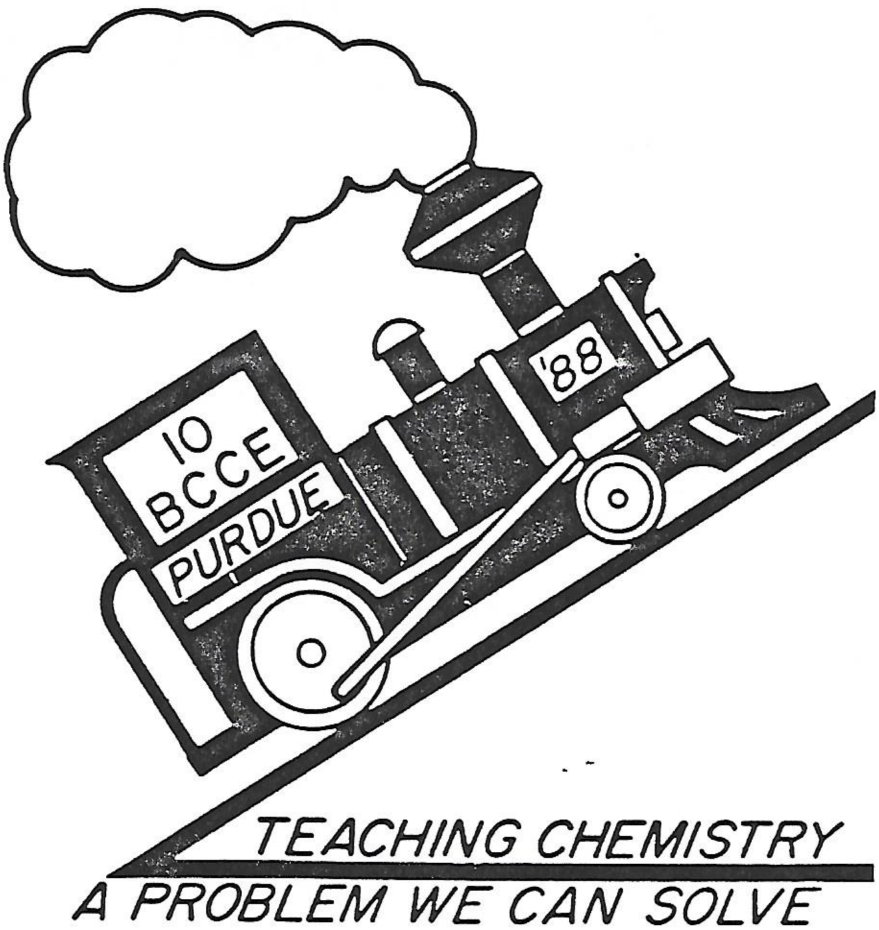

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Lockheed, Hewlett Packard, IBM, AT&T) employed 41 teachers in their laboratories for eight weeks during the summer. The Lawrence Hall of Science helped these teachers to convert their work experience into one of value and enrichment for their students. In IISME, industries are the initiators, the Lawrence Hall of Science staff are the facilitators, and the teachers are the translators and deliverors to students.

In three years, nearly 300 teachers have had the opportunity to work in a wide range of industries (including chemical companies such as DuPont and Dow Chemical). The results of the program are impressive, as are the expansions of the program to academic year inservice activity, including a telecommunications network, curriculum development efforts, and a credit-bearing academic year institute to promote further professional development. Research work will now attempt to measure the impact of this type of teacher inservice on students. Results, particularly as they pertain to chemistry teachers, will be discussed.

027 LEARNING CHEMICAL THERMODYNAMICS AT SCHOOL: THE USE OF NON-INTERACTIVE VIEWS TO INTERPRET ENERGY CHANGES. A. F. Cachapuz and I. P. Martins, University of Aveiro, Aveiro 3800-Portugal.

This study was conducted to investigate the nature of representations held by high school students about the processes of energy changes associated with chemical reactions. The sample comprised 29 Portuguese students from different grade levels in which the topic had been taught at different degrees of elaboration. The procedure consisted of a one-to-one interview involving four experimental tasks organised according to two main dimensions: exothermic/endothermic and spontaneous/non-spontaneous reactions. Data was analysed using the method proposed by Erickson (1979). The results revealed several patterns of misconceptions: (a) most of the students used sequential or local ways of reasoning when explaining energy changes, (b) the role of the activation energy was misunderstood, (c) subjects' representations of the chemical change rarely involved an articulated perception between structural and energetic components, (d) the lack of conceptual differentiation between energy and temperature. These ideas consistently emerged for different task contexts. They were also identified for both instructional groups thus suggesting little conceptual change. Possible reasons explaining the alternative conceptions identified are discussed in terms of cultural, psychological (memory capacity) and instructional aspects. Implications for teaching and suggestions for future research are included.

MONDAY MORNING, AUGUST 1, 1988
CHEMISTRY FOR CHILDREN (AND ADULTS)

028 BOILING HOT -- FREEZING COLD: A LECTURE DEMOMSTRATION PROGRAM FOR MIDDLE SCHOOL CHILDREN. Frederick H. Juergens, Chemistry Department, University of Wisconsin-Madison, Madison, Wisconsin 53706.

This program of ten demonstrations is organized around the theme: changes of state. It is intended as a teaching vehicle, to broaden children's concepts of the terms "boiling" and "freezing". Though most of the demonstrations are spectacular,