CHEMISTRY EDUCATION: RESEARCH AND PRACTICE IN EUROPE
2000, Vol. 1, No. 1, pp. 17-26

THE PRACTICE OF CHEMISTRY EDUCATION (INVITED CONTRIBUTION)
Methods and issues of teaching and learning

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SHOULD CHEMISTRY LESSONS BE MORE INTELLECTUALLY CHALLENGING?

Received: 19 September 1999

ABSTRACT: Empirical studies on students' alternative conceptions have shown that students often make mistakes as they are misled by alternative conceptions, for instance when they are not aware of the shift of meaning which some chemical terms have undergone in the course of time. Such terms are ambiguous since they contain an old and a new aspect. Oxidation has shifted from an oxygen transfer to an electron transfer reaction. Neutralization was defined as a reaction between an acid and a base which consume each other; nowadays it is seen as a proton transfer reaction producing water. A chemical reaction was seen as proceeding in one direction, while in principle all chemical reactions reach equilibrium as a result of a forward and a reverse reaction. The periodic table has developed from a table of elements as substances to a periodic table of atoms of the elements. To solve problems in these areas proved to be quite a challenge for many students. Some arrived at correct answers, others did not. However, the majority tried to find reasonable solutions. To make chemistry lessons more attractive needs more intellectually demanding courses and a new teaching culture in which teachers are interested in what students think and from that basis help them to develop their understanding of chemistry. [*Chem. Educ. Res. Pract. Eur.*: 2000, *1*, 17-26]

KEYWORDS: *alternative conceptions; chemical terms; shift of meaning; oxidation; neutralisation; chemical reaction; chemical equilibrium; periodic table*

INTRODUCTION: CHEMICAL TERMS AND CONCEPTS

Chemistry teaching is open to criticism in many countries. In Germany most students at high school level drop chemistry as soon as they get the opportunity. At university level only very few students enroll for chemistry. Some argue that the more able students might even find chemistry boring. Can research on students' alternative conceptions help to improve chemistry teaching?

An important part of the scientific language are scientific terms. They contain most of the information of a scientific text. Terms are labels for concepts (Figure 1). Scientific language undergoes changes, like any other spoken language. It often happens that new ideas are added to an old concept. The meaning behind labels changes whereas the labels remain (Figure 2). Chemists often use the different definitions in parallel. As a result terms become ambiguous since they contain an old and a new aspect. Students may associate a label with its historical meaning because this is what they first learnt in chemistry courses. Moreover, in some cases a label was chosen to indicate the original meaning of the term. This paper summarizes information about alternative conceptions students develop when they apply their knowledge of concepts that have shifted their meaning.

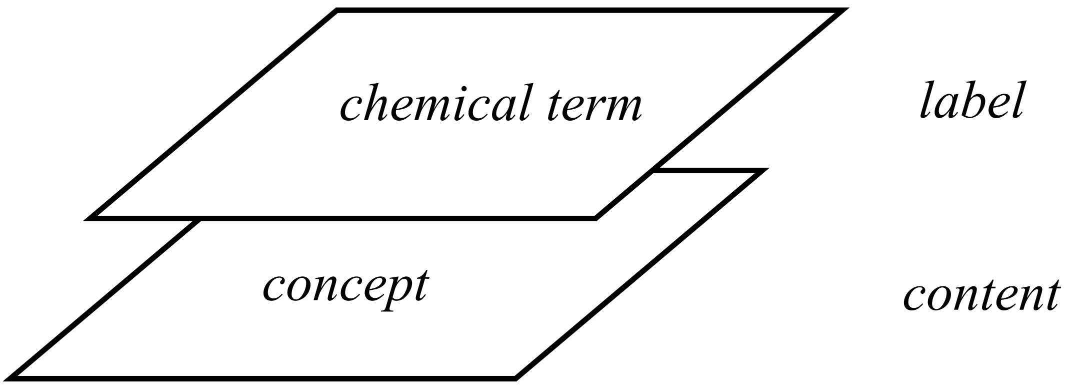

FIGURE 1. Relation between a term and the underlying concept.

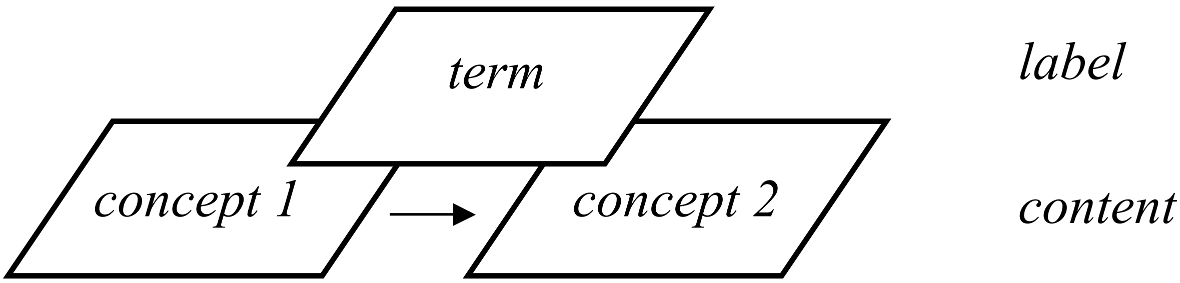

FIGURE 2. *Shift of meaning of a term.*

SHIFTING THE MEANING OF CHEMICAL TERMS

Rise and fall of the oxygen dynasty

Oxidation was originally defined by *Lavoisier* as a reaction in which oxygen is involved, forming oxides. *Lavoisier* referred to substances that can be observed in the laboratory: oxygen and oxides. The modern definition describes processes between invisible particles. Electrons are transferred from one particle to another, or particles undergo changes in oxidation numbers (Figure 3).

If particles lose electrons or if there is an increase in the oxidation number, this process is called oxidation. At the same time, a reduction takes place: other particles accept electrons or undergo a decrease in their oxidation numbers. The whole process is described by a new term: redox reactions. The concept oxidation has thus been broadened. Oxygen does not necessarily take part in this process: there are many redox reactions in which oxygen is not involved. The reaction between magnesium and hydrochloric acid is one example.

(1) $Mg (s) + 2 HCl (aq) \rightarrow MgCl_2 (aq) + H_2 (g)$

In this reaction electrons are transferred from magnesium atoms to H_3O^+ ions. The oxidation number of magnesium increases while the oxidation number of hydrogen decreases. However, the reactions between hydrochloric acid and magnesium oxide

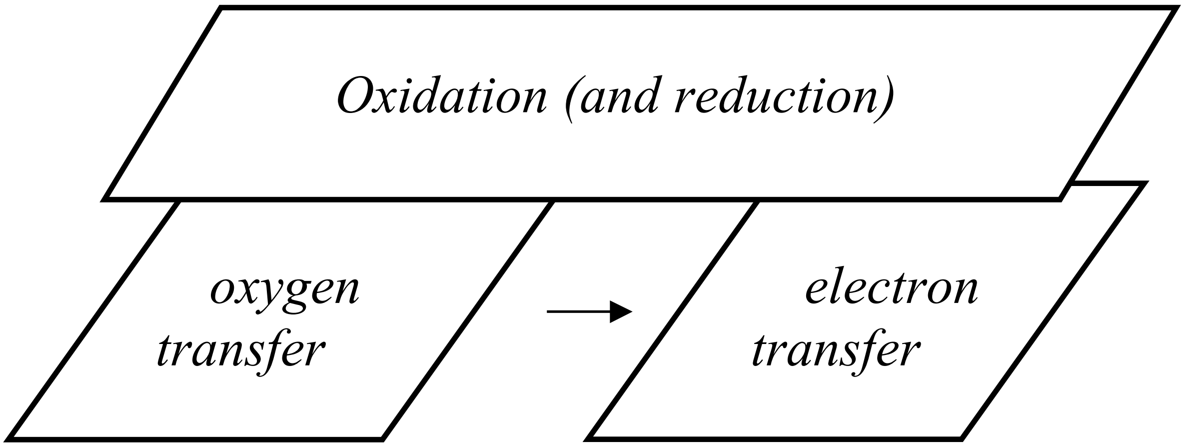

FIGURE 3. Shift of the meaning of the term oxidation.

(2) $MgO (s) + 2 HCl (aq) \rightarrow MgCl_2 (aq) + H_2O (l)$

or between hydrochloric acid and magnesium hydroxide

(3) $Mg(OH)_2 (aq) + 2 HCl (aq) \rightarrow MgCl_2 (aq) + 2 H_2O (l)$

are, although oxygen is involved, not redox reactions: no electrons are transferred and no changes in oxidation numbers occur.

The difficulties of senior high school students with the described problems became clear when they were confronted with the following problem (Schmidt, 1997 b):

Item 1

In three separate experiments dilute hydrochloric acid reacts with magnesium, magnesium oxide and magnesium hydroxide. In which case(s) does a redox reaction occur?

(1) Reaction of dilute hydrochloric acid and magnesium
(2) Reaction of dilute hydrochloric acid and magnesium oxide
(3) Reaction of dilute hydrochloric acid and magnesium hydroxide

[A] Response (1) only is correct
[B] Response (2) only is correct
[C] Response (3) only is correct
[D] Responses (2) and (3) only are correct

Many students chose the incorrect answer D, although they had the correct answer A in front of them (Table 1). Students' comments show that they had good reasons for it. Here is a typical comment from a 13th grade elementary course student:

> *The syllabi "ox-" or "-hydrox-" are foolproofs for red-"ox"-reactions. Any other answer would be absurd.*

TABLE 1. *Distribution of students' answers among the options for item 1: Grades 12 and 13 elementary courses (e) and grades 12 and 13 advanced courses (a).*

	Options chosen (%)					
Course	[A]*	[B]	[C]	[D]	No answer	Number of students
e	29	12	7	31	21	58
a	47	15	6	23	9	53

* The asterisk suggests "correct answer". Elementary course (e) requires three chemistry lessons per week, advanced course (a) five to six lessons per week (Schmidt, 1992).

With an 11th grade course a group discussion on how to solve item 1 was conducted. The discussion started by reading the stem of item 1 and asking students to explain the term redox reaction (I = interviewer, S 1, S 2 ... = student 1, 2 ...).

I: *What does that mean to say, a redox reaction?*
S 1: *If a reduction and an oxidation occur simultaneously.*
I: *What is an oxidation, then? And a reduction that occurs simultaneously?*
S 2: *Oxidation means donation of electrons, reduction acceptance of electrons.*

In the next phase the students were invited to openly vote which answer they regarded as correct. It resulted in an even split between those who opted for A and D. The interviewer first asked students who opted for A (the correct answer). Nobody responded. Then those who opted for D were addressed:

I: *Did anybody opt for D? Could you give reasons for your answer?*
S 3: *For me all redox reactions involve oxygen ... in an oxidation reaction oxygen is added and in a reduction it is removed. Oxygen has to be present in one of the reactants. In the reaction of magnesium oxide and magnesium hydroxide* [with hydrochloric acid] *oxygen is donated ... and accepted at the same time.*

After a while the interviewer turned again to the students who were in favor of A.

I: *... Nobody opting for A any more?*
S 4: *D is not correct because the question is not whether oxygen is donated or accepted but whether electrons are accepted or donated.*

Student 3 overgeneralized the old definition by *Lavoisier* and concluded that oxygen is involved in any redox reaction. The reasoning developed thus far gives the impression that these students have clarified their views about redox reactions to their own satisfaction. Their comments are, therefore, indicators for alternative conceptions (Selley, 1997).

Does neutralisation really mean neutral?

Neutralisation used to be defined as a reaction between two substances, an acid and a base, which consume each other. This is what the label neutralisation indicates. It stems from the Latin word neuter meaning neither of the two.

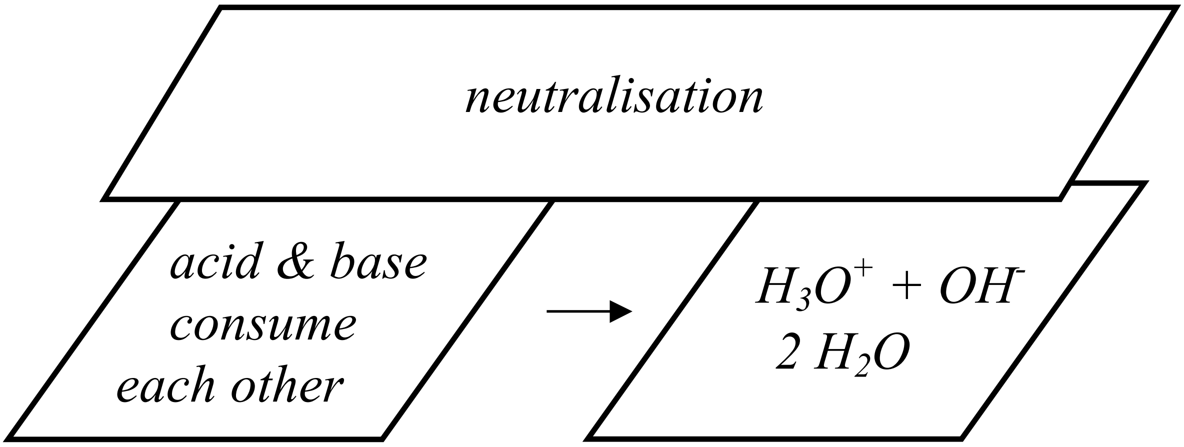

FIGURE 4. *Shift of meaning of the term neutralisation.*

Brønsted's theory states that acids and bases are particles exchanging protons. A neutralisation is an acid-base reaction between H_3O^+- and OH^--ions producing water.

(4) H_3O^+ (aq) + OH^- (aq) & 2 H_2O

Acid and base do not consume each other completely, they react to a great extent. The concentration of H_3O^+- and OH^--ions in a neutral solution is very small, approximately 10^{-7} mole/l. Nevertheless, neutral no longer means neither of the two.

Neutralisation is another example where a shift of meaning has occured (Figure 4):

If weak acids are involved as in the reaction between acetic acid and sodium hydroxide, two bases OH^- and Ac^- (Acetate ions) compete according to the equations (4) and (5) for the H_3O^+ ions:

(5) H_3O^+ (aq) + Ac^- (aq) & H_2O (l) + HAc (aq)

Consequently, more H_3O^+ ions are used up which means that the solution becomes basic. Thus, a reaction between equimolar amounts of acetic acid and sodium hydroxide does not yield a neutral solution. Can such a reaction be called a neutralisation? This is (Schmidt, 1997a) how students in a group discussion reasoned about it (S 1, 2 ... = student 1, 2 ...):

S 1: *You can't ... call this a neutralisation if we have a slightly basic pH value.*
S 2: *... but the product is only slightly basic, so why not call it neutralisation.*
S 3: *... Neutralisation does ... not necessarily ... mean that in the end the pH value is neutral.*
S 4: *You have to ... define a little more precisely ... is it ... having a neutral pH value or ... acid and base being balanced.*
S 5: *... well, I could neutralise only partly and thus it would be right to call this a neutralisation.*
S 4: *... it is not good [to call this a neutralisation]. We had two solutions and made a relatively neutral one from them ... but in the end we have a pH value that is not neutral.*
S 2: *... neutralisation is not like either dead or not dead. It can happen ... gradually. It is the way towards neutrality.*

In order to learn more about students' difficulties item 2 was given to senior high school students (Schmidt, 1991).

Item 2

An aqueous solution of 1 mole of NaOH (sodium hydroxide) was added to an aqueous solution of 1 mole of CH_3COOH (acetic acid). Which of the following statements is true about the resulting solution?

[A] It contains more H_3O^+ ions than OH^- ions
[B] It contains fewer H_3O^+ ions than OH^- ions
[C] It contains as many H_3O^+ ions as OH^- ions
[D] It contains neither H_3O^+ ions nor OH^- ions

Table 2 shows the result.

TABLE 2. *Distribution of students answers' among the options for item 2: Grades 12 and 13 elementary courses (e) and grades 12 and 13 advanced courses (a).*

	Options chosen (%)					
Course	[A]	[B]*	[C]	[D]	No answer	Number of students
e	3	26	34	21	16	124
a	6	30	34	21	10	90

Among the incorrect answers was a preference for distractors C and D. Apparently, some students came to the conclusion that neither H_3O^+ nor OH^- ions remain because the ions neutralised each other. Here is a written students' comment for distractor D:

There are neither H_3O^+ nor OH^--ions, because the reaction is a neutralisation.

It can be seen that this student used the term neutralisation although it is not mentioned in the stem. Some students considered the dissocation of water so that as many H_3O^+ ions as OH^- ions resulted at the end of the reaction. This is a comment of a student who chose distractor C:

There are as many H_3O^+ ions as OH^- ions because the molar proportions are equal and neutralise each other so that only H_3O^+ and OH^- ions from the equilibrium reaction of water remain.

Obviously students did not realize that chemists nowadays have a more detailed view of the neutralisation concept as compared with the original idea that was termed 300 years ago.

The chemical reaction: a single or double journey?

Chemical reactions were originally associated with observable phenomena and understood as processes in which reactants are converted into products having different physical properties. According to the modern view a chemical reaction is described on the particle level as a dynamic equilibrium between two opposite reactions, the forward and the reverse reaction (Figure 5).

All chemical reactions are in principle reversible and eventually reach equilibrium when the rates of the forward and the reverse reaction are equal. This explains that in an

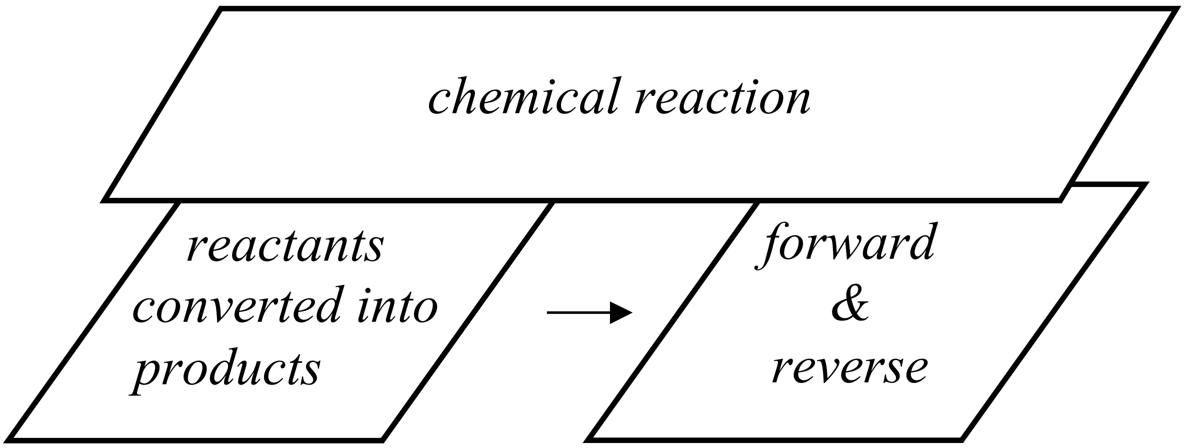

FIGURE 5. *Shift of meaning of the term chemical reaction.*

equilibrium state all the original reactants, as well as the resulting products, are present. From a macroscopic point of view the system is at rest.

Research has shown (van Driel et al. 1998) how difficult it is for students to understand

- the dynamic nature of chemical equilibrium,
- why a reaction does not proceed to completion although all conditions are given for the reaction to continue.

Bergquist and Heikkinen (1990) report that students often describe the chemical equilibrium in terms of oscillating reactions.

The periodic table: From elements to atoms of elements

Originally the periodic table was a dis[play of the chemical elements according to the regularities in the properties of elements (Table 3). Chemical elements with similar chemical properties were grouped together in chemical families or groups. Later it was realized that the arrangement of the elements in the Periodic Table can easily be justified by the structure of the atoms (Table 4).

Today chemists use the Periodic Table of Elements to reflect its original meaning, but also to reflect contemporary understanding of atomic structure (Figure 6). The Periodic Table has developed from a table of elements as substances to a Periodic Table of atoms of the elements. This shift of meaning can confuse students and can give them the idea of using the term element as a synonym for atom (Schmidt, 1998).

CONCLUSION

Three concluding remarks for the implications for teaching and research:

(1) Students may have difficulties in understanding chemical terms that have changed their meaning. Figure 7 summarizes the examples from the preceding discussion. It shows that in chemistry a shift of meaning often follows a pattern:

TABLE 3. *Short format for the periodic table (according to Lothar Meyer 1870).*

I		II		III		IV		V		VI		VII		VIII	
a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b
H														He	
Li		Be		B		C		N		O		F		Ne	
Na		Mg		Al		Si		P		S		Cl		Ar	
					Sc		Ti		V		Cr		Mn		Fe Co
K		Ca		Ga		Ge		As		Se		Br		Kr	
	Cu		Zn		Y		Zr		Nb		Mo		Tc		Ru Rh
Rb		Sr		In		Sn		Sb		Te		I		Xe	
	Ag		Cd		La		Hf		Ta		W		Re		Os Ir Pt
Cs		Ba		Tl		Pb		Bi		Po		At		Rn	
	Au		Hg		Ac										
Fr		Ra													

TABLE 4. *Arrangements of electrons in the shells of atoms of selected main group elements.*

period	element	Number of electrons in each shell				
		1	2	3	4	5
1	H	1				
	He	2				
2	Li	2	1			
	Be	2	2			
	B	2	3			
	:	:	:			
	Ne	2	8			
3	Na	2	8	1		
	Mg	2	8	2		
	Al	2	8	3		
	:	:	:	:		
	Ar	2	8	8		
4	K	2	8	8	1	
	Ca	2	8	8	2	
	Ga	2	8	18	3	
	:	:	:	:	:	
	Kr	2	8	18	8	

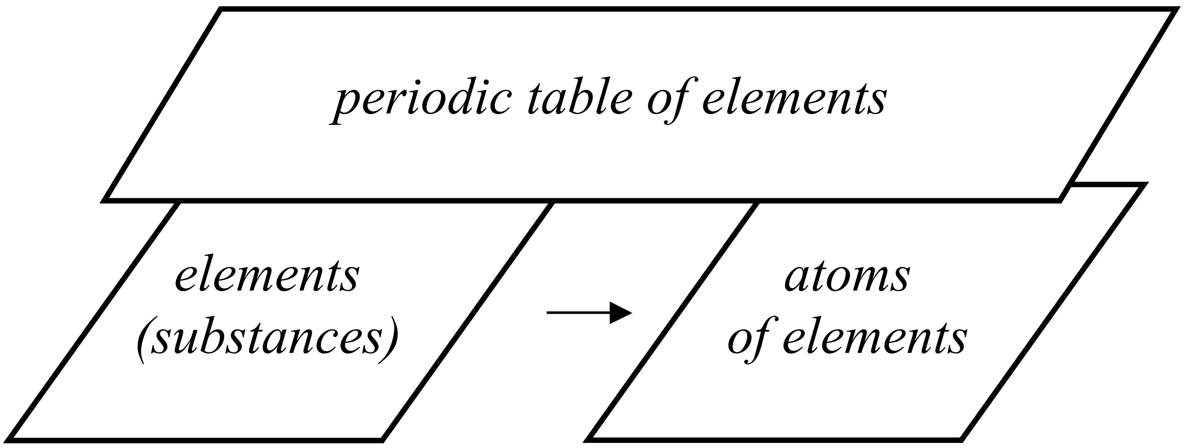

FIGURE 6. Shift of meaning of the term Periodic Table of Elements.

- On the left side of Figure 7 the former macroscopic definitions are emphasized. Students first learn about them in their introductory chemistry courses.
- The right side of Figure 7 points to the current definitions of chemical terms. These refer to the particle level. Students learn about them as they continue to study chemistry in advanced courses. Here is the place to reflect the pattern according to which a shift of meaning occurs.

(2) Students very often develop alternative conceptions. These may cause communication problems as long as they are unknown to teachers. Research in chemistry education tries to identify students' problems. This knowledge gives teachers ahead of time the opportunity to

	oxidation/reduction	
oxygen transfer	➔	electron transfer
	neutralization	
acid and base consume each other	➔	$H_3O^+ + OH^-$ & $2H_2O$
	chemical reaction	
reactants converted into products	➔	forward & reverse reaction
	periodic table of elements	
arrangement of elements (substances)	➔	arrangement of atoms of elements

FIGURE 7. *Shift of meaning of chemical terms.*

plan teaching strategies needed to overcome students' alternative conceptions. Students should not be left alone with their problems. It is the classroom where alternative conceptions have to be discussed. However, it should be mentioned here that the more the research is domain-specific, that means the more it identifies the chemical aspects of students' problems, the closer it comes to the needs of teachers.

(3) Most students who took part in our research projects tried their best to make sense of chemistry. Some arrived at correct answers, others did not, but had good reasons for doing so. It indicates that students think. This is exactly what we want them to do. The main thing in chemistry lessons should be that students give reasons for their strategies and answers to problems. In the first instance correct answers are not as important. Of course in the end we want students to arrive at correct solutions. Those who cleverly solved a problem incorrectly may be on the way to a correct answer. Chemistry is an experimental and an intellectual science. To make chemistry lessons more attractive we need courses which are more intellectually challenging and give students ample opportunities to exercise their creativity. It also needs a new teaching culture in which teachers are interested in what students think, and from that basis help them to gain an understanding of chemistry.

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