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Document Version:
Publisher's PDF, also known as Version of record

Citation for published version:
Ben-Zvi, R, Silberstein, J & Eylon, BS 1987, 'Students' visualization of a chemical reaction', *Education in chemistry.*, vol. 24, pp. 117-120.

Total number of authors:
3

Published In:
Education in chemistry.

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Students' visualisation of a chemical reaction

Research work pinpoints student difficulties in understanding chemical reactions.

There seems to be an agreement between chemistry teachers and researchers in the area of science education that chemistry is a difficult subject especially for young students. Many reasons have been cited: chemistry deals with abstract concepts;[1] stoichiometric calculations are difficult;[2,3] any given problem in chemistry deals usually with many variables and thus overloads students' working memory[4] and the language of chemistry is difficult for the novice.[5] In spite of this, a review of textbooks for elementary chemistry, shows that chemical equations are usually introduced at a very early stage as a shorthand description for chemical reactions.

A task analysis of a comparatively simple equation, such as

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$$

shows that in order to 'read' the equation correctly, one should master the following:
1. The structural aspects of chemical reactions. This includes the chemical structure of reactants and products. In the example mentioned above, the following components should be understood:

- *The structure of a molecule – an element.* The symbols 'O_2' or 'H_2' denote a molecule, namely an autonomous unit in which two atoms are bonded together.
- *The structure of a molecule – a compound.* The symbol 'H_2O' denotes a molecule of a compound with two O–H bonds.
- *The nature of the gaseous state.* The symbol (g) means, that the elements (or the compound) in the gaseous state consist of many scattered molecules in constant movement.

2. The interactive aspect of a chemical reaction. A chemical reaction is a process of bond breaking and bond formation.
3. The dynamic aspect of a chemical reaction. A chemical reaction is a time-dependent process involving a dynamic interaction of many particles.
4. The quantitative aspects of the reaction.

It is not expected that all these aspects would be mastered by students at the first stages of their studies. However, it is important to characterise the exact nature of students' views concerning each of these aspects. A long term study was undertaken in order to find out to what extent students who study an elementary course in chemistry are familiar with the ideas mentioned above. This study consisted of two parts. The first dealt with aspects *1* and *2* and was constrained only to molecular substances. Some of the results were published elsewhere[6] and relevant findings are summarised below. The second part dealt with reactions involving ionic substances and focused on aspects *2* and *3*. Aspect *4* was not included in our research.

The question arises to what extent the difficulties of beginning students diminish towards the end of their high school studies in chemistry. To illuminate this question we report in the third part some preliminary results of a study conducted with advanced high school students.

Part 1

The first part of the research was conducted among 337 students aged 15+ from 11 classes in academic high schools in Israel. All students had studied chemistry for about seven months. The main relevant findings were the following.

1. The structural aspects of chemical reactions: The reaction used in the study was the decomposition of gaseous Cl_2O into its elements.

- *The structure of a molecule – an element.* Most of the students in our sample (97 per cent) represented a molecule of oxygen as one unit consisting of two connected atoms.
- *The structure of a molecule – a compound.* About a quarter of the sample seemed to have an additive rather than interactive view of a compound. For example, they represented the compound Cl_2O as consisting of two fragments – Cl_2 and O.
- *The nature of the gaseous state.* Only 10 per cent of the students represented $O_2(g)$ by many scattered molecules of oxygen. The percentage of correct answers was, however, much higher (68 per cent) when the task asked explicitly for the description of an element in the gaseous state. This is an indication that after seven months of study, the chemist's language was not freely accessible to students. When students were asked to represent a compound (Cl_2O) in the gaseous state, only 34 per cent of them succeeded. About 20 per cent of the sample described the gaseous compound by one single unit consisting of two fragments – Cl_2 and O. The rest (46 per cent) either drew one molecule with a correct structure, or many units with incorrect structure. It was evident from interviews with students that none of them thought that a gas consists of one molecule. However, when the two aspects were required *ie* the need to consider that each molecule has an internal structure and that there are many such molecules, they disregarded one or both of the aspects.

2. The interactive aspect of a chemical reaction: It seems obvious that if students have problems with any of the aspects mentioned above (or with all of them) they cannot grasp the interactive nature of a chemical reaction. This conclusion can be supported by quotations of students' answers to the following question:

> In a reaction between the elements N_2 and O_2, new substances may be formed. For each of the following indicate whether they are possible products of a chemical reaction. a. N_2O; b. NO; c. NO_2; d. N_2O_5; e. N_2 together with O_2. Explain your answers.

Two types of difficulties were identified. Difficulties due to focusing on single units are exemplified by

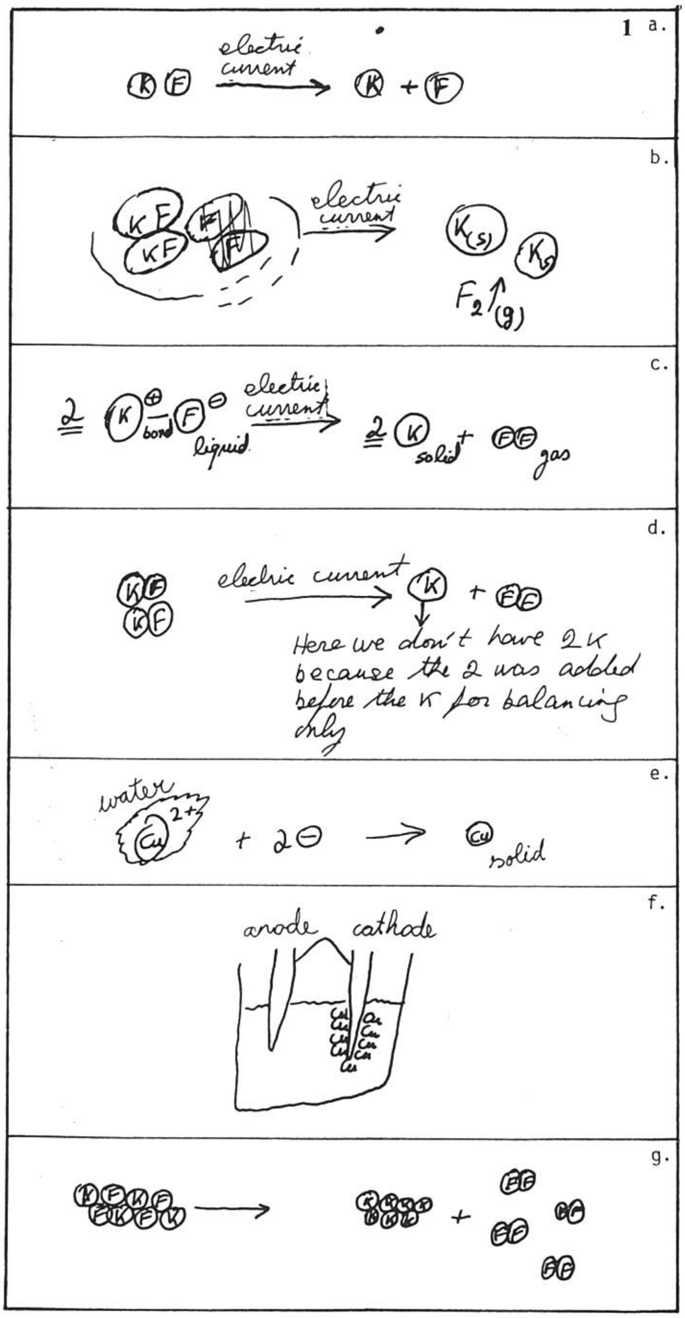
> N_2O_5 cannot be formed – we had N_2 and O_2. Where from did we get three additional oxygen atoms?

> NO cannot be formed. According to the law of conservation of mass, the mass of the product is less. That is against the law.

> NO_2 can be formed. It is possible that nitrogen, for some reason and because of the reaction, will disappear within the vessel.

Difficulties due to an additive view of structure were also revealed

> NO cannot be formed. We had O_2 which cannot be decomposed and N_2 which also cannot be decomposed.



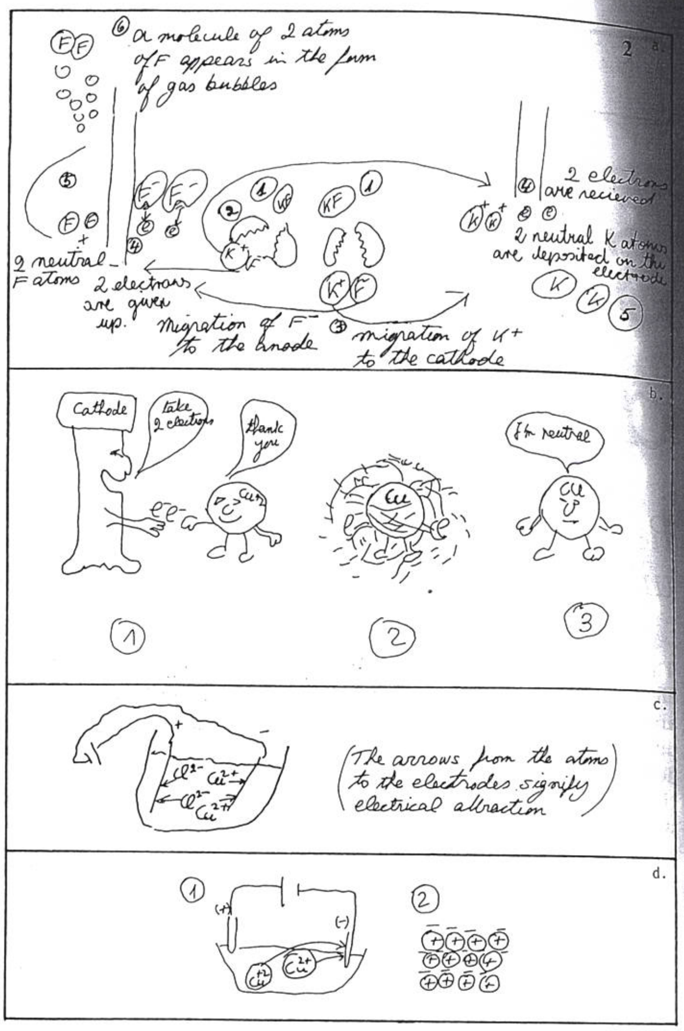


Fig. 1. Typical drawings by students who represented the reactions by a static microscopic representation (the drawings are exact copies of students' work with translation of their remarks).

Fig. 2. Typical drawings by students who represented the reactions by a dynamic microscopic representation (the drawings are exact copies of students' work with translation of their remarks).

N_2O_5 cannot be formed – these are not the elements we had at the beginning. We had $N_2 + O_2$ and not $N_2 + O_5$.

An analysis of students answers showed that 40 per cent of the sample did not distinguish between N_2O_2 and $N_2 + O_2$ as possible products for the reaction.

The results of the first part showed that many students who study elementary chemistry are unable to understand correctly a simple chemical equation even after more than half a year of study. Moreover, some of them seem to hold wrong ideas both about structure and about the interactive nature of chemical reactions. Similar results were reported by Yaroch.[7]

Part 2

The second phase was designed to widen the scope of our understanding of students' conceptions about reactions. In this phase the questions dealt with electrolysis reactions.

The sample consisted of 994 students from 35 classes (10th grade) who had studied chemistry for about half a year. They were given the following equations:

1. $2KF(l) \rightarrow 2K(s) + F_2(g)$
2. $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$

For each of them they were asked to represent their meaning by drawings.

Students' answers were analysed and the drawings for each equation were categorised in the following way.

I: *Lack of understanding of the equation.* This category consisted of meaningless or missing drawings.

II: *A macroscopic understanding of the equation.* Drawings in this category did not involve any use of models. For example, a drawing of a glass full of liquid with two electrodes inserted in the liquid, with or without the names of reactant and products.

III: *A static microscopic representation.* Students were classified in this category if they drew models representing the constituents of the equation without giving any indication of something happening during the process. *Figure 1* shows some typical drawings classified in this category. One distinction among the drawings is whether a single or many units are represented (drawings *a–e* vs *f–g*). In some drawings there was a one to one 'translation' of each symbol in the equation (drawings *a–e*). In other drawings, such as example *f*, only one stage of the process is represented.

The examples shown also represent typical misconceptions about the structure of matter. For example, KF(s) is represented by two atoms (*a*) or by two molecules (*b*). K(s) is represented by single atoms (*a, b, c* and *d*). Of special interest is drawing *b*, where the student drew two atoms of K each of them in the solid state. Similarly, in drawing *d* the student wrote explicitly that 'here we don't have two K because the 2 was added before the K for balancing only'.

IV: *A dynamic microscopic representation.* Drawings were classified into this category if they fulfilled at least one of the following conditions: (*i*) representation of the reaction as occurring in well defined stages, *eg* before the reaction and after the reaction, and (*ii*) an attempt to show movement of ions towards the electrodes.

The drawings in this category can be classified (as was done for category III) into those which dealt only with one particle and those with many particles. Typical examples are given in *Fig. 2*. Drawings *a* and *b* are dynamic representations of single particles while in drawings *c* and *d* many particles are shown. An elaborate description of the reaction as taking place in six well defined stages is shown in drawing *a*. The student denoted the stages by numbers. The 'molecule' of KF (stage 1) is decomposed into the two ions (stage 2) which then move towards the respective electrodes (stage 3). The F ions give up electrons to the anode (stage 4) and neutral atoms are formed (stage 5). At the same time, the K ions extract electrons from the cathode (stage 5) and neutral atoms are formed. The two neutral F atoms are combined to form molecules which leave the solution (stage 6).

In drawing *c* the movement of ions is stressed both in drawing (by arrows) and in writing. Drawing *d* represents two stages of the reaction: the ions being attracted to the electrode and the resulting product with its metallic structure.

Educational implications

Many textbook authors, especially in the last two decades, have come to the conclusion that the introduction of models can help students to get a better insight into aspects of structure and process in chemistry.

Unfortunately, a full description of a chemical reaction is rather cumbersome and therefore, in many cases, authors tend to describe only that part of the reaction which seems relevant to the presented idea. For example, if the formation of NaCl(s) is discussed in the context of ion formation, very often it is represented by

$$Na\cdot + \cdot\ddot{\underset{\cdot\cdot}{Cl}}: \rightarrow NaCl$$

This representation may lead the student to think that one atom of sodium reacts with one atom of chlorine to form one pair of NaCl.

Two additional examples are presented

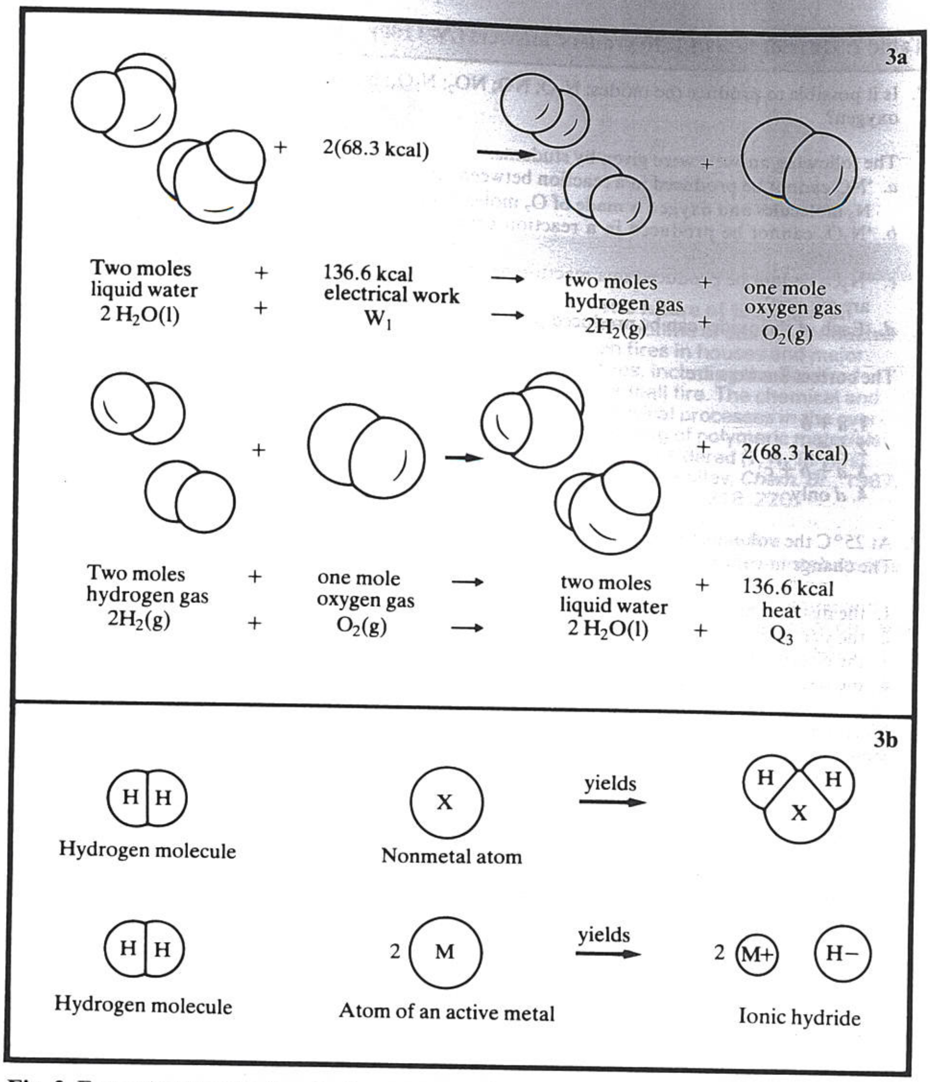


Fig. 3. Examples from textbooks for representations of a reaction by models.

in *Fig. 3*. In the first example, the author was very careful to tell the students that the two molecules of H_2O serve to represent two moles of water. It is plausible to assume however, that the impact of the illustration may be much stronger than that of the text. In the second example the author wanted to stress the difference between metallic and non-metallic hydrides. He may have succeeded in establishing this point, but at the expense of amplifying the misconception that both a metal and a non metal consist of one atom.

The study of students' misconceptions, parts of which were described in this article, led to the development of a new textbook for 10th grade students in Israel. One of the main purposes of the authors was to try to help students overcome learning difficulties. The book uses models very extensively and both structure and reactions are represented in a way similar to that used by Pauling[8] in *General chemistry*. Namely, representing many units, and stressing the dynamic nature of reactions by trying, as far as possible, to indicate movement of particles.

The new textbook[9] was studied by about half of the students who responded to the questionnaire described above (N=454). The other students (N=540) studied a currently used textbook which was not geared to dealing with the misconceptions described.

Table 1. Distribution of drawings representing *1.* $2KF(l) \xrightarrow[\text{current}]{\text{electric}} 2K(s) + F_2(g)$

2. $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$

Category	Control (N=201)	Experimental (N=169)
I Lack of understanding of the equation	23.4	0.6
II Macroscopic understanding of the equation	1.5	3.0
III Static microscopic representation		
a. single units	59.7	52.7
b. many units	6.0	5.3
IV Dynamic microscopic representation		
a. single unit	2.5	10.1
b. many units	7.0	28.4

As was mentioned above, students' drawings for each of the equations were classified into one of the categories described. Table 1 shows the distribution of categories in the experimental and control groups. Only students who were consistent in both drawings were included in the analysis.

The results show that in spite of all the efforts, more than half of the experimental group still adhered to a static representation using models of single particles. The percentage in the control group was very similar. However, differences do exist between the two groups. About a quarter of the control group were classified into category I, exhibiting lack of understanding of the equation, whereas only one student in the experimental group was classified into that category. On the other hand, more than a third of the experimental group succeeded in representing the dynamic nature of the reaction as compared to only about 10 per cent of the control group.

Part 3

As part of another study, 1100 students who studied chemistry at the advanced level (12th grade) were given a multiple choice questionnaire about a variety of topics studied during three years in high school. Three items, relevant to the present article

Table 2. Distribution of 12th graders' answers (N=1100)

1. Is it possible to produce the oxides: N_2O; NO; NO_2; N_2O_4; N_2O_5 in a reaction between nitrogen and oxygen?

The following answers were given by students:

a. 'NO cannot be produced in a reaction between nitrogen and oxygen because nitrogen is made of N_2 molecules and oxygen is made of O_2 molecules'.

b. 'N_2O_3 cannot be produced in a reaction between nitrogen and oxygen because an O atom is missing'.

c. 'N_2O_5 cannot be produced in a reaction between nitrogen and oxygen because three atoms of O are missing'.

d. 'Each of the oxides can be produced provided the necessary conditions exist'.

The correct answers are:

	percentage
1. $a+b$	2.1
2. $b+c$	5.3
3. $a+b+c$	4.2
4. d only	88.1

2. At 25°C the volume of 1 gram of water is 1 ml. At 100°C the volume of 1 gram of water is 1671 ml. The change in volume is due to the difference between:

	percentage
1. the distance between the atoms in the molecules	7.4
2. the size of the atoms in the molecules	1.6
3. the distance between the molecules	89.6
4. the size of the molecules	1.3

3. The following sentences concern various substances at room temperature and pressure. Which of the sentences is correct?

	percentage
1. Solid iodine, $I_2(s)$, consists of one molecule in which 2 iodine atoms are linked by a chemical bond	15.4
2. Solid sodium, Na(s), consists of only one atom which is not linked to other atoms	6.1
3. Gaseous ammonia, $NH_3(g)$, consists of molecules in which the nitrogen atom is linked by chemical bonds to each hydrogen atom	71.2
4. Gaseous carbon dioxide, $CO_2(g)$, consists of a carbon atom, C, linked to an oxygen molecule, O_2	6.9

are given in Table 2.

The results indicate that even at the end of their high school studies some students still have difficulties with some of the basic aspects involved in understanding a chemical reaction.

Conclusion

The data presented in this article show the difficulties which students have in understanding the nature of chemical reactions. Even a textbook which was specifically designed to stress various aspects of the dynamic nature of reactions was only partly successful. Furthermore, some of the difficulties were detected even with advanced high school students. Since the concept of chemical reactions is considered to be an important objective of chemistry teaching, teachers should be made aware of students' difficulties in this area. In particular, the inherent difficulty of presenting the dynamic nature of reactions in textbooks means that teachers must be instrumental in teaching this aspect of chemical reactions.

Acknowledgement: We wish to thank Mrs Michal Rapson for her help in the analysis of the results.

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