# Theories, principles and laws

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a small scale (tube 35 mm dia. × 200 mm long) discourages the demonstrator from scaling up the experiment.

## Avoiding trauma

In the discussion of disasters we try to avoid emotional trauma and to date we have not mentioned either the Abbeystead methane explosion or the *Challenger* disaster. However, time passes and events become history. The next time that the lecture is given the use of hydrogen and oxygen for the main propulsion system of the space shuttle will lead into the use of oxygen as an oxidant in place of air. This introduces the demonstration of the oxy-hydrogen flame and the production of limelight. In another lecture we have demonstrated the explosion of these gases with oxygen in 500cm$^3$ PET pop bottles but here time is running out so we return to the idea of using the $H_2/O_2$ explosion and introduce, with a nautical flavour, a one litre steel gas cannon which fires a ball bearing into a ship target on wheels. The distance moved by the target is a measure of the pressure generated in the explosion. The distances moved by the target when the cannon is filled with methane or acetylene/oxygen mixtures are also found and these are related to the energies of combustion of equal volumes of these gas mixtures. However naval practice continued to use gunpowder and the gas explosions are compared with the effect of a similar mass of gunpowder fired from a further cannon (which needs a firearms certificate).

It is now time, or past time, to return to the *Hindenberg*. Explaining that the airship was the pride of the German civil air service we divulge that it was in fact not static electricity that caused the disaster but an incendiary device. Inviting a volunteer to use a magneto to detonate a bag full of a hydrogen and oxygen mixture provides a suitably noisy end to the lecture. After which it only remains to admonish the audience not to play with electricity or explosive gases knowing full well that it is just that that has inspired many good scientists.

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**Reference**

1. *J. Chem. Ed.*, 1985, **62**, 1105.

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### R. Ben-Zvi, B. Eylon and J. Silberstein

# Theories, principles and laws

*Experienced chemists shift easily between macro and micro aspects of chemistry, but the conceptual demands this places on students can be overwhelming.*

'Chemistry is like a majestic sky scraper. The concrete, secure foundation of chemistry consists of countless experimentally observed facts. The theories, principles and laws developed from these observations are like an elevator which runs from the bottom to the top of the edifice'.[1]

This is no doubt a picturesque way of showing the interrelationship between facts and theories in the teaching of chemistry. The assumption, or rather, the hope of the chemistry teacher is that the elevator of theories, principles and laws carries his students with him. We report here part of an exhaustive study undertaken in order to investigate this assumption.

Chemistry is considered by many high school students to be one of the most difficult subjects they study. Much has been said about the abstract nature of chemical concepts and the inability of students who have not reached the 'formal' stage (as defined by Piaget) to cope with these concepts.[2,3] Students' problems become acute when they are asked to perform stoichiometric calculations using the mole concept.[4,5,6] Here, in addition to demonstrating understanding of chemical reactions, the student must be able to apply a thorough understanding of the principles involved in ratio and proportion calculations.

The root of many difficulties that beginning chemistry students have appears to be deficient understanding of the very basic concepts of the atomic model and how it is used to explain macroscopic properties and the laws of chemistry. For example, in a study investigating problems encountered by students in learning the mole concept, 530 students (ages 15–16) were given a multiple choice questionnaire, concerning various aspects of stoichiometry, after they had studied chemistry for one year.[7]

To the question: 'What is the mass of one atom of hydrogen?' 38.5 per cent of the sample answered one gram, and to the question 'What is common to a mole of $H_2$ and a mole of $H_2O$?' 21 per cent gave the answer 'The number of $H_2$ molecules'. These responses seem to indicate that many students hold a wrong picture of the nature of the atom and the structure of compounds. This is not surprising; even a superficial overview of the development of the atomic theory is enough to convince us that the concepts involved are very difficult. It should be remembered that, as recently as 1902, Wilhelm Ostwald warned his fellow chemists not to take the concept of atoms too seriously. Our students, however, cannot avoid using the word atom right from the first lesson in chemistry and even prior to it. The question remains, 'What picture of the atom do they have in mind?' The ancient view of atoms is manifested, for example, in the words of the Greek philosopher Anaxagoras: '... for as gold is made up from gold dust, so all the world is an aggregation of minute bodies, the parts of which are like the whole'.[8] This idea is the most intuitive view of atomicity. If we accept Branford's claim[9] that 'the history of each individual development is a brief compendium of the history of the race' then it seems that the first notion of the atomic model formed in the minds of students may in many aspects be similar to the ancient Greek model. To many of these students an atom of copper will be viewed as a small piece of the solid metal while an atom of mercury will mean a small drop of the liquid.

During their studies, it is hoped that this picture of the atom will gradually develop into a more sophisticated picture and that the atomic theory would allow a meaningful learning of chemistry as suggested[10] in a handbook for teachers: 'To them (the students), indeed, the atomic theory is of the greatest value, not simply as a kind of mnemonic but as a real and tangible model of matter of all kinds, upon which the imagination of young minds can begin to work.'

What makes the study of chemistry so difficult is that students usually do not have enough time to 'get used' to function at the atomic–molecular level and are asked, very early in their studies, to think in terms of moles of particles. An analysis of many basic textbooks in chemistry shows that students are expected to move very quickly from one level of description to another. Many basic chemistry books start with a description of various *phenomena* – the three states of matter, the classification of pure substances into compounds and elements, the law of definite composition *etc.* Very soon a *model* is introduced in order to unify and explain the phenomena. Teachers are encouraged to use concrete models to help their students visualise the abstract concepts and the students' minds are channelled to think about single particles – oxygen is one molecule composed of two balls, water is an entity composed of three balls *etc.* A chemical reaction may also be explained by means of models; for example see *Fig. 1*.

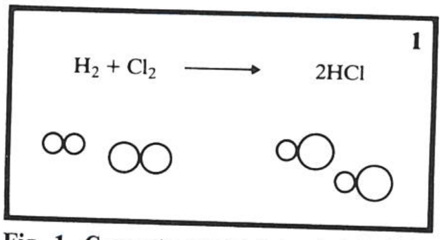

**Fig. 1. Concrete model intended to help visualisation of a reaction.**

However, in spite of this insistence on single models, students are told at a very early stage that they should think about millions and millions of particles since chemistry is not the science of single entities, but of *moles* of atoms or molecules.

The teacher, therefore, goes from the macroscopic level to the atomic level – the atom and molecule and back to the macroscopic, or rather a multi-atomic level (the third level of description). This big jump is usually made in a very short time at the very beginning of the course; it is our claim that not many students are able to follow their teacher 'in his climb from floor to floor'. Some of the students will not understand what is meant by the atomic–molecular model and others will not realise the need to think about a multitude of particles.

Another aspect of the difficulties students face during this early stage in their study is the language of chemistry. Chemists have been using a shorthand notation for many years. This is, of course, a very good and efficient way for communicating one's ideas, provided that both the writer and the reader understand the symbols in the same way. 2H, to the chemist, means two individual atoms of hydrogen, while $H_2$ means a molecule in which two atoms are bound by a covalent bond. We tend to forget that the novice is not very familiar with the ideas of structure and bonding and the difference between atoms and molecules is not very clear in his or her mind. These problems are confined to the atomic–molecular level of description.

When the third level of description is introduced things become more difficult. In English, an A always stands for A, B for B and so on. In chemistry, on the other hand, similar symbols may have different meanings, dependent on the use of the symbol. For example, 'He' stands for a non-reactive gas which is less dense than air and is named helium. Very soon 'He' is no longer a label for the gas with its specified macroscopic properties, but stands for a single atom of helium or, in the terminology of CHEMStudy (1965), a monoatomic molecule of helium. 'O' stands for an atom of oxygen, but since (says the teacher) oxygen exists in nature as a diatomic molecule we refer to it as $O_2$. If that is not enough, during the next series of lessons one reads in the textbook that $2H_2$ (meaning 4g of hydrogen) combines with $O_2$ (32g of oxygen) to form 2 moles of water – $2H_2O$. The authors of modern textbooks try to help the students to distinguish between one molecule and a multitude of molecules by adding in parentheses the states of matter (s) (l) and (g) whenever the multi-atomic level is discussed. The problem remains. How many students really think about the kinetic molecular theory whenever they come across $H_2(g)$?

To summarise, we claim that there are three interwoven aspects of chemistry which make its study very difficult, especially for beginning students. One is the abstract and non-intuitive nature of the concepts involved. Another is the need to coordinate the previously discussed levels of description in using the atomic model, and the third aspect is that of communication, since similar symbols in chemistry have different meanings according to the level of description being used. These basic difficulties are not always manifested in ordinary teaching settings since students may adopt a set of algorithms, proceed through their studies in chemistry and even succeed in the examinations without understanding the basic concepts thoroughly.

Our research was undertaken in order to find out what problems students have with each of the aspects mentioned. Namely, how they understand and view some of the concepts involved in the atomic model, how they use the various levels of description and what difficulties they have with the language chemists use. In this article we want to answer the following questions:

- When chemical symbols are used, what levels of description are triggered in students' minds (macroscopic level, the atomic–molecular level, the multi-atomic level)?
- Assuming that students use the various levels of description, how do they represent the atomic and multi-atomic aspects of matter?

**Table 1. Categories used in the analysis.**

| | |
|---|---|
| *1.* Cu(s) | *a.* phenomenology only |
| | *b.* a single atom |
| | *c.* a single molecule |
| | *d.* many particles. |
| *2.* $H_2O(l)$ | *a.* phenomenology only |
| | *b.* single model – atoms of a molecule |
| | *c.* single incorrect model |
| | *d.* single correct model |
| | *e.* many particles – atoms |
| | *f.* many particles – incorrect models of molecules |
| | *g.* many particles – correct models |
| *3.* $Cl_2(g)$ | *a.* phenomenology only |
| | *b.* a single atom |
| | *c.* a single molecule |
| | *d.* many atoms |
| | *e.* many molecules |

The sample consisted of 275 10th grade students. The students came from eight classes in two academic high schools in Israel. These classes, of varied ability levels, were taught by five teachers. The average age of the students was 15; all of them had studied chemistry for at least six months. All of the students used the same textbook, *Chemistry for high school.*[11] During this six month period the students were introduced to states of matter, properties of solutions including electrical conductivity, chemical reactions in the gaseous state and reactions in solutions – precipitation and redox reactions. They were given the appropriate models, *ie* atoms, molecules and ions were used to explain the phenomena. They were also taught how to balance chemical equations and how to perform stoichiometric calculations using the mole concept.

All students were given the following question:

> Describe in every possible way (using words, drawings, symbols, *etc.*) what you understand from the following:
>
> *1.* Cu(s)
>
> *2.* $H_2O(l)$
>
> *3.* $Cl_2(g)$

Samples of the responses were read in order to establish a categorisation scheme for classifying the answers. All of the responses were then independently read and categorised by two of the authors according to the scheme developed. If no agreement could be reached on a particular response in comparing the judgements it was not included in the analysis. The categories given in Table 1 were used to analyse the responses.

The category of 'atoms' for $H_2O(l)$ and $Cl_2(g)$ (2*b*, 2*e* and 3*d*) included answers such as 'water is made up of two hydrogen atoms and one oxygen atom' or '$Cl_2(g)$ consists of two atoms of chlorine'. Incorrect models for water (2*c* and 2*f*) were answers such as 'a water molecule consists of a molecule of hydrogen linked to an atom of oxygen'.

The only source of information in this study was the collation of student answers volunteered in response to the symbols presented to them. Taking this into account the scoring was, however, done according to the sentences and drawings used by the students. It is quite possible that there is a gap between the mental picture the students had and the words they used and therefore the findings only suggest possible difficulties students may have. For example, it is possible that the students whose answers were categorised under 'atoms' for $H_2O(l)$ and $Cl_2(g)$, had a molecular picture in mind,

**Table 2. Percentage of students presenting macroscopic properties ($N$=249).**

| | Solid | Liquid | Gas |
|---|---|---|---|
| Macroscopic properties only | 54.9 | 8.1 | 6.9 |
| Others | 45.1 | 91.9 | 93.1 |

but one cannot be sure of that, and therefore these answers were categorised separately in order to distinguish them from others who used the molecule concept explicitly.

The use of open-ended questions in our study was intended to elicit as many free responses from the students as possible. As a result, many unexpected misconceptions became apparent. On the other hand, as was already mentioned, there is no way to ascertain whether a student who described only phenomena does not function at the level of models or whether this is a result of the interpretation that only such properties were asked for.

Table 2 summarises the percentage of students who gave as an answer only the properties of each substance *vs* all the rest.

It can be seen that while more than 90 per cent of our sample gave some sort of a model for the liquid or the gas, only about 45 per cent did so for the solid. The data presented divides the sample in a very arbitrary manner into those who did or did not present a model. The majority of the students, however, gave some macro properties for water together with the model, while not as many described any properties of the gas.

The fact that the examples used were of substances familiar from everyday life seemed to have a high influence on the responses. The finding that most of the students provided models for the water and the gas is probably due to the curriculum they use, in which the structure of the water molecule and the kinetic theory of gases are both stressed during the first half year of their chemistry course.

On the whole it seems that students are able to function both on the macroscopic and the model levels, at least for some of the material that they study in chemistry. The main question, of course, is what sort of models do they use in order to explain the phenomenology.

Table 3 is a cross-tabulation of students' responses for the liquid and gas questions in terms of the three levels of description.

As is apparent only 8.4 per cent of the students presented a multi-atomic picture both for the liquid and the gas. 64.5 per cent of our sample presented a picture which led us to believe that they may see, in the notation $H_2O(l)$ or $O_2(g)$, a representation of one particle only. To them, the use of (l) or (g) did not seem to mean that a multitude of molecules is indicated. This result may show translation difficulties, but may also be due to conceptual misunderstanding.

One of the most surprising findings was the fact that after about six months of studying chemistry, many students in our sample had in mind (or rather on paper) an incorrect picture of the structure of a molecule. The following examples may serve to illustrate these misconceptions.

> Water consists of hydrogen, a molecule which appears in nature, and of oxygen.
>
> A compound made up of hydrogen, which in the gaseous state consists of two atoms, and also of oxygen. (This was accompanied by a drawing showing a diatomic molecule of hydrogen and at some distance an atom of oxygen.)
>
> A water molecule which consists of an oxygen atom (O) and two hydrogen atoms ($H_2$) in the liquid state:
>
> $H_2(g) + O(g) \rightarrow H_2O(l)$
>
> $H_2$ is hydrogen gas, O is oxygen, both appear in the aqueous state and form water.

The statements cited seem to indicate that students feel that the water molecule consists of two distinguishable fragments ($H_2$ and O). Such a view of the structure of a compound is congruent with the idea that in a chemical reaction the fragments are 'glued' to each other. This 'additive' view was volunteered by some students (see for example the third quotation above).

We categorised statements about the structure of the molecules, similar to those quoted above as representations of a 'glue' model for the $H_2O$ molecule. The distribution on the various models for water is summarised in Table 4.

As can be seen from the table we can be fairly sure that only 71 per cent of the members of our sample knew that, in a water molecule, two hydrogen atoms are linked to the oxygen atom. This corresponds to the data presented in the introduction in which about 20 per cent of the students stated that a water molecule contains a unit of $H_2$.

Can we infer from the students' responses what mental pictures they form of the atom? More than a quarter of our sample wrote sentences similar to the following:

> $Cu(s)$ is one atom of copper in the solid state.
>
> $H_2O(l)$ is a molecule of water in the liquid state.
>
> $Cl_2(g)$ is two atoms of chlorine in the gaseous state.
>
> At room temperature the chlorine molecule is in the gaseous state.

Some even went further and claimed that:

> $Cl_2(g)$ is a diatomic molecule which has an irritating smell.
>
> $Cl_2(g)$ is one molecule which has a yellow colour.

This seems to indicate that our assumption may be true. Students seem to retain, for a long period of time, the intuitive model of an atom as being a small portion of the substance.

**Table 4. Distribution of student models for water ($N$=229).**

| Model | Percentage of students |
|---|---|
| Atom – atoms | 15.3 |
| Glue (single or many) | 12.7 |
| Molecule – molecules | 71.0 |

If indeed this is the case it seems quite natural that in the minds of these students, a compound is viewed in an additive rather than interactive manner. It should be kept in mind that the shorthand notation which textbooks use from the very beginning refers to the water molecule, for example, as $H_2O$ and not as HOH and so helps to establish the wrong additive notion.

Our results seem to indicate that students have problems with even the very basic concepts which are prerequisites for an understanding of chemistry. The structure of a molecule and the idea that chemistry deals mainly with a multitude of particles are just two of these basic concepts.

At this stage, it is, of course, possible to assume that at least some of the results cited above are an artifact due to students' inability to express themselves precisely and present in writing the mental picture they have. Moreover, from the results of this study it is not clear which difficulties are merely caused by students' inability to translate.

## Discussion

This article summarises the results of a study undertaken in order to find out which mental pictures are triggered in the students' minds by chemical symbols. Most students are able to think in terms of symbols and models, but in many cases the models they use seem to indicate some very serious misconceptions.

Many students seem to think that an atom or a molecule of an element has the macro properties which characterise the element (hardness for a solid, odour and colour for a gas). About 13 per cent of the sample presented an additive model for the molecule of a compound (a water molecule equals $H_2 + O$) and 70–80 per cent represented substances by single particles.

These results suggest that many beginning science students have a distorted mental picture of the atomic model. To improve instruction in this topic it is important to identify the factors which influence this mental picture. In general, the mental picture developed in a particular topic can be regarded as an embodiment of factors

**Table 3. Distribution of description levels used by students ($N$=248; numbers indicate percent of total sample).**

| Gas<br>Liquid | Phenomenology | Single unit | Many units | Total |
|---|---|---|---|---|
| Macroscopic | 2.0 | 4.5 | 1.6 | 8.1 |
| Single unit | 4.5 | 64.5 | 10.2 | 79.2 |
| Many units | 0.4 | 3.3 | 8.4 | 12.1 |
| Total | 6.9 | 72.3 | 20.2 | |

which are roughly divided into external and internal factors.

The external factors include the information being learned and the sources which mediate this information (*ie* textbooks, teachers *etc*). There are several features of the atomic model which make it difficult: it deals with abstract concepts (*ie* atoms and molecules), includes several levels of description which may be confusing and it is communicated by symbols with multiple possible interpretations. The sources which mediate the information sometimes do not consider its intrinsic difficulty and may even increase the confusion. *Figure 2* illustrates such a case; volumes of gases are represented by *single* molecules. Other examples can be found in many popular textbooks.

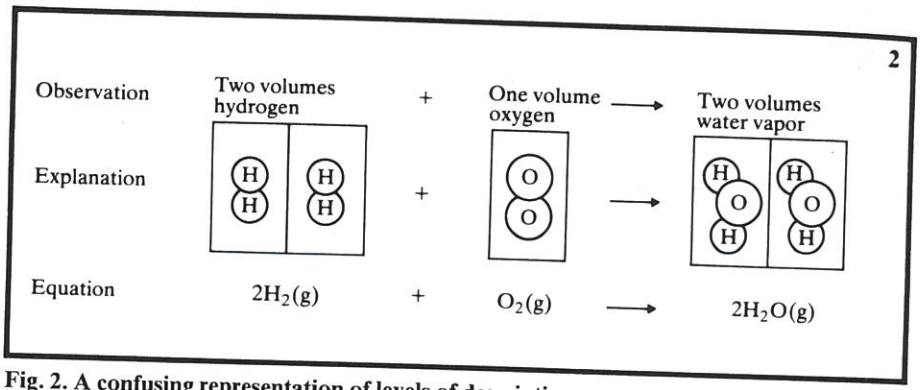

**Fig. 2. A confusing representation of levels of description.**

As to the internal factors, Ausubel[12] emphasises that meaningful learning is always based on a relevant set of concepts already held by the student. If students have a set of misconcepts to build upon, it is quite possible that they distort new information so that it will fit their framework. This set of concepts that the student already holds *ie* the mental picture, is based on previous learning and intuitions which may be misleading. In the case of the atomic model the view which is in essence similar to the 'Greek atom' is an example of such an intuition which may cause a distorted assimilation of the atomic model rather than meaningful accommodation.[13]

Another important internal factor is that of cognitive characteristics which influence the way in which the existing mental picture interacts with the external factors to determine the new mental picture of the student. For example, a cognitive characteristic may be that of 'mental capacity'.[14] It turns out that this capacity is limited to several units of information, and therefore a person can process simultaneously only a limited amount of information. This factor may be very important for determining how students can deal with the different levels of description discussed in this article which need to be processed simultaneously in many cases.

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J. E. Packer

# Difficulties with stoichiometry

*A lack of understanding of the principles of measurement, ie what a quantity is, what a unit is and the relationship between them, is a root cause of students' problems with stoichiometry.*

In 1980 an article on titrimetry calculations[1] in this magazine prompted several letters to the editor[2-8] in which different teaching approaches were formulated. Frazer and Servant have recently examined the methods which students with passes in GCE A-level chemistry actually use,[9] and also the methods and terminology used by chemists in the workplace.[10] A significant and alarming conclusion of their first paper was an overall lack of student competence. In this study they identified four reasonably distinct methods of doing a calculation, gave two straightforward problems to each of 244 students, and analysed the methods used and success rate of each method.

The overall success rate was abysmal, 27 per cent of students obtaining correct answers on one problem and five per cent on the other. Many students used no identifiable method, and these students had a 100 per cent failure rate.

The implication of this is that the methods being taught by chemistry teachers are either inadequate or inappropriate to provide students with the necessary understanding and skills to solve such problems.