Student-generated submicro diagrams: a useful tool for teaching and learning chemical equations and stoichiometry

Bette Davidowitz[a]*, Gail Chittleborough[b] and Eileen Murray[c]

Received 13th March 2009, Accepted 8th May 2010
DOI: 10.1039/C005464J

This paper reports on a pedagogical approach to the teaching of chemical equations introduced to first year university students with little previous chemical knowledge. During the instruction period students had to interpret and construct diagrams of reactions at the submicro level, and relate them to chemical equations at the symbolic level with the aim of improving their conceptual understanding of chemical equations and stoichiometry**.** Students received instruction in symbol conventions, practice through graded tutorial tasks, and feedback on their efforts over the semester. Analysis of the student responses to formative test and summative exam items over consecutive years indicates that there was a consistent improvement in the abilities of the various cohorts to answer stoichiometry questions correctly. The responses provide evidence for diagrams of the submicro level being used as tools for reasoning in solving chemical problems, to recognise misconceptions of chemical formulae and to recognise the value of using various multiple representations of chemical reactions connecting the submicro and symbolic levels of representation. The student-generated submicro diagrams serve as a visualisation tool for teaching and learning abstract concepts in solving stoichiometric problems. We argue that the use of diagrams of the submicro level provides a more complete picture of the reaction, rather than a net summary of a chemical equation, leading to a deeper conceptual understanding.

Keywords: chemical equations, stoichiometry, submicroscopic diagrams, representations

Introduction

Chemical diagrams are used to represent chemical information, to help describe an idea, provide an explanation, present a visual image, to make predictions and deductions and to form hypotheses. They can be static or dynamic, two or three dimensional, or single-particle vs. multiple-particle (Chittleborough and Treagust, 2008). Diagrams of the submicro level include representations of molecular, atomic and sub-atomic particles, which may be depicted as a single atom, a particle or an array of particles. Expert chemists are able to interpret these diagrams; however, they pose a significant intellectual challenge for the novice (Johnstone, 1993; Gabel, 1999; Treagust and Chittleborough, 2001). While previous research into the difficulties of stoichiometry and chemical equations have recommended an emphasis on visual approaches using diagrams of the submicro level, the difficulties persist (Ben-Zvi *et al*., 1987; Sanger, 2005). In an attempt to help students better understand chemical equations and stoichiometry, this paper reports on an intervention programme where instruction and assessment focussed on students drawing the basic representations of the submicroscopic level of matter – including atomic, molecular and particle representations of the reactants and products. The students' resulting abilities to draw and interpret diagrams of the submicroscopic level in assessment tasks were investigated.

[a] *Chemistry Department, University of Cape Town, South Africa*
E-mail: Bette.Davidowitz@uct.ac.za
[b] *Faculty of Arts and Education, Deakin University, Australia*
E-mail: gail.chittleborough@deakin.edu.au
[c] *Chemistry Department, University of Cape Town, South Africa*
E-mail: Eileen.Murray@uct.ac.za

Diagrams of the submicro level

A descriptive tool, such as a diagram or an image, can provide the learner with a way of visualizing the concept and hence developing a mental model for the concept (Gabel, 1998). However, the diagram can also lead to misconceptions, as indicated by Ben-Zvi *et al.* (1988) by depicting a reaction at the atomic level with single particles where in reality many particles are present. The value of a diagram in making the link with an abstract concept depends on its being consistent with the learners' needs and being pitched at the learners' level of understanding (Giordan, 1991). According to Mayer (2002) students learn by active selection, organisation and integration of information from auditory and/or visual inputs. Chittleborough and Treagust (2008) reported that students with a limited background in chemical knowledge struggled to comprehend the diagrams of the submicroscopic level, which is not surprising considering their lack of familiarity with the symbolism and conventions often used without explanation in chemical diagrams.

Johnstone's three levels of representation, namely macro, submicro and symbolic (1993) provide a useful framework for understanding and teaching chemistry. Expert chemists can easily move between the three levels, but research has shown that the submicro level presents difficulties for novice learners. For example Nurrenbern and Pickering (1987) used diagrams depicting the submicro level of chemistry, and

Table 3.5 Information Contained in a Balanced Equation

Viewed in Terms of	Reactants $C_3H_8(g) + 5O_2(g)$		→	Products $3CO_2(g) + 4H_2O(g)$	
Molecules	1 molecule C_3H_8 + 5 molecules O_2		→	3 molecules CO_2 + 4 molecules H_2O	
Amount (mol)	1 mol C_3H_8	+ 5 mol O_2	→	3 mol CO_2	+ 4 mol H_2O
Mass (amu)	44.09 amu C_3H_8	+ 160.00 amu O_2	→	132.03 amu CO_2	+ 72.06 amu H_2O
Mass (g)	44.09 g C_3H_8	+ 160.00 g O_2	→	132.03 g CO_2	+ 72.06 g H_2O
Total mass (g)	204.09 g		→	204.09 g	

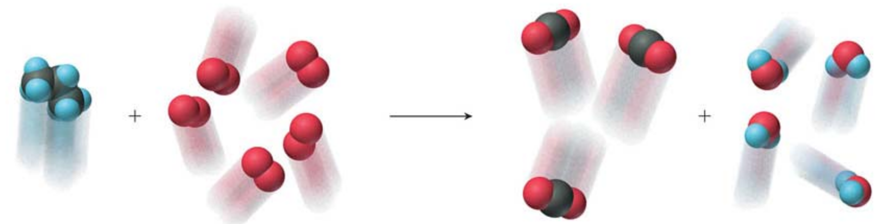


Fig. 1 Information contained in a balanced equation (from M.S. Silberberg, Chemistry: The molecular nature of matter and change, 5th ed., McGrawHill, 2009, p. 110, reproduced with permission of The McGrawHill Companies).

showed that while students could solve algorithmic chemistry problems, they had difficulties in answering conceptual problems covering the same topics. Students' ability to solve problems using algorithms without the reasoning and processing skills that demonstrate a concomitant conceptual understanding has been widely documented in the literature (Niaz and Robinson, 1992; Nakhleh *et al,* 1996; BouJaoude and Barakat, 2000; Sanger, 2005, Papaphotis and Tsaparlis, 2008). Without an understanding of the theory of the particulate nature of matter and the requisite bonding, students are often unable to predict the structure of elements and compounds, resorting to macroscopic properties and everyday expressions to predict structure (Ben Zvi *et al.*, 1988).

Most authors of introductory chemistry text books use diagrams depicting all three levels of representation. In recent years there has been an increasing number of diagrams of the submicro level in the text, in the problem sets that appear at the end of each chapter, and in the multiple-choice test banks accompanying the text *e.g.* Silberberg (2009). Commonly, the diagrams of the submicro level show circles of different sizes and colours representing either single atoms, *e.g.* helium, or groups of atoms, *e.g.* water. While submicro diagrams in text books are almost invariably depicted in colour, diagrams drawn in black and white are usually provided with a key to assist learners to interpret them.

The use of diagrams in explaining chemical equations and stoichiometry

A chemical equation summarises the net changes occurring in a reaction, and does not show details such as the mechanism, the spectator species or the reagent in excess. Novices see balancing simple equations as the application of a set of rules, and may not make the connection between the symbolic representation of the reaction and the actual chemical transformations that are occurring (Laugier and Dumon, 2004). In addition, they may have difficulties in producing and interpreting equations due to a lack of conceptual resources (Taber and Bricheno, 2009). Ben-Zvi *et al.* (1987) analysed students' answers, including students' diagrammatic representations of the structural aspects of chemical reactions, and reported that many students were *"unable to understand correctly a simple chemical equation",* with some students holding *"wrong ideas about both the structure and the interactive nature of chemical reactions"* (p. 118).

The chemical equation and mole concept allow chemists to interpret reactions in terms of balance sheets representing the quantities of matter. A chemical equation summarises a reaction; it does not represent the submicroscopic nature of the reacting components. Textbook authors often include diagrams containing multiple representations of the information contained in a balanced equation (Fig. 1).

These diagrams may appear simple and obvious to the expert chemist, but for a novice they contain much unfamiliar or new information about the chemical reaction at both the submicro and symbolic levels, presented in multiple representational formats. According to Laugier and Dumon (2004) chemical explanations draw on our experiences at the macroscopic level, which are real and tangible, and then jump to the submicro level that are *"invisible chemical entities"* (p. 329) with little development or meaning given to the submicro representation. Ben Zvi *et al.* (1987) described an intervention using a textbook that intentionally emphasised models, structures and diagrams to stress the *"dynamic nature of reactions"* (p. 119) to overcome the commonly reported learning difficulties. The authors reported some improvement in the number of students being able to successfully represent the dynamic nature of the reactions. Kelly and Jones (2008) examined students' understandings of animations of the submicroscopic level and concluded that it was difficult for students to transfer their understanding of the macroscopic level to submicroscopic representations, suggesting that more guidance was needed.

Even when students manage to manipulate the coefficients in a balanced equation, they often fail to connect the multiple views referred to above (Yarroch, 1985). In any given cohort of students there will be a vast range of abilities of students in respect of balancing an equation and understanding the implied meaning in terms of macroscopic and submicroscopic levels (Huddle and Pillay, 1996; Laugier and Dumon, 2004). Some students will have a full understanding of the different meanings of chemical symbols and coefficients, while others will simply attempt to balance the equation by trial and error. Niaz and Robinson (1992) suggest that even the trial and error method could pose difficulties for students, as it places demands on their reasoning ability as well as on their facility at handling ratios and proportions.

The challenge in interpreting the symbols in a chemical reaction for students who may have difficulties in distinguishing the difference between coefficients and subscripts was the subject of a study by Marais and Jordaan (2000). The authors used an instrument consisting of multiple choice items to test students' abilities to interpret the common examples of symbolic notation such as $[NO_2]$ and $2NO_2$. While 41.9% of the cohort was able to identify square brackets in $[NO_2]$ as representing the molar concentration of NO_2, only 7.4% of them knew that $2NO_2$ referred to two molecules (or two moles) of NO_2. The authors suggested that chemistry teachers should realise that students may have difficulties in interpreting symbols and urged them to specifically teach the symbolic understanding that all chemists use as part of their discourse.

The chemical equation, which lies at the heart of reaction stoichiometry, has been identified as a difficult topic for learners (Hackling and Garnett, 1985; Huddle and Pillay, 1996; Fach *et al*, 2007). A thorough understanding of stoichiometry requires more than the ability to follow an algorithm (Herron, 1975; Ben-Zvi *et al*, 1988), since stoichiometric coefficients represent more than a simple mathematical method for balancing equations. Novice students may be able to use algorithms to solve problems in stoichiometry without necessarily understanding the concepts that underpin this important topic in most first-year chemistry curricula (Niaz and Robinson, 1992; Huddle and Pillay, 1996; BouJaoude and Barakat, 2000; Papaphotis and Tsaparlis, 2008).

Students drawing diagrams of submicro level to represent chemical equations and solve stoichiometric problems – a pedagogical approach

Being able to solve problems involving chemical equations and stoichiometry requires both applying rules and having an understanding of the concepts that give the rules meaning (Huddle and Pillay, 1996). The chemical equation is not the same as a diagram of the submicro level, which may include representations of molecular, atomic and sub-atomic particles. Focussing on this difference is a pedagogical approach that requires active student-centred problem-solving tasks. These can provide opportunities for students to demonstrate their understanding which may inform future teaching. Huddle and Pillay (1996) advised that:

> *"It is only when students become active and have to think that learning occurs. Construction of knowledge is a process that has to be undertaken by the learner."* (p. 74).

It is important for students to understand the information implicit in a chemical equation, since the balanced equation forms the basis of stoichiometry. Traditionally teaching of chemical equations and stoichiometry has focussed on the symbolic level of representation relying heavily on algorithms (Ault, 2001) to solve the various types of problems. Despite the increase in frequency of submicro diagrams in introductory text books, there has been little research into the use of student-generated drawings of the submicro level when teaching chemical equations and stoichiometry. Tien *et al*. (2007), for example, have adapted the 'Model-Observe-Reflect-Explore' (MORE) thinking frame to promote students' reflection and revision of personal mental models of the submicroscopic level so that they are consistent with macroscopic observations.

The research literature indicates that students' difficulties in understanding chemical equations are sustained and consistent over a long period of time, despite the identification of pedagogical approaches that have been shown to make a difference to students' understandings (Ben-Zvi *et al.*, 1987). Airey and Linder (2009) investigating ways of knowing physics, refer to students developing the skill of using specific disciplinary representations as part of the discourse to represent their knowledge. The disciplinary discourse occurring around the use and meaning of multiple representations is seen as essential to achieve discursive fluency – explained as**:**

> *"a process through which handling a mode of disciplinary discourse with respect to a given disciplinary way of knowing in a given context becomes unproblematic"* (Airey and Linder, 2009, p. 33).

A *chemical epistemology* – that is, an understanding of the knowledge of how chemical ideas are built, and an understanding of the way of knowing about chemical processes, involves developing a similar level of confidence and ease with the discipline knowledge (Chittleborough, 2004). The submicro drawings are specific disciplinary representations used with an intentional pedagogical approach to promote discourse and understanding to develop a chemical epistemology. For this study, which investigates the use of submicro diagrams to probe student difficulties with writing and balancing chemical equations and stoichiometry, students were required to interpret diagrams of the submicro level and to relate these diagrams to symbolic representations as well as construct their own diagrams. In this way the diagrams can serve as explanatory tools providing means to promote reasoning and thinking (Treagust and Harrison, 1999). The research questions being examined were:

RQ1 How can student-generated drawings of the submicro level provide insights into their understanding of chemical equations and stoichiometry?

RQ2 What are the common difficulties of solving chemical equations and stoichiometry problems identified from students' drawings of the submicro level?

RQ3 What evidence is there that *drawing* diagrams can help students to reason and solve problems concerning chemical equations and stoichiometry?

Table 1 The questions answered by various cohorts over the period of the study

Year	No of students	Questions
2007 test 1	111	2
2007 mid-year exam	111	1 and 3
2008 test 1	164	4a
2008 mid-year exam	164	4b
2009 test 1	117	5
2009 mid-year exam	120	5

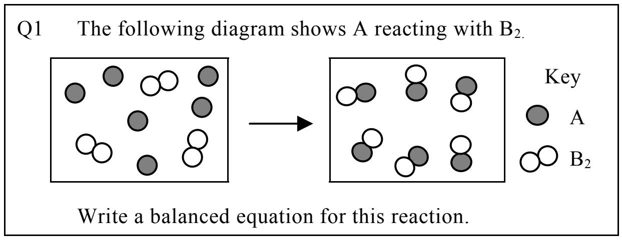


Fig. 2 Diagram used with question 1

Methodology

Sample

The participants in this study were three cohorts of first-time entering students registered in the General Entry for Programmes in Science (GEPS) at a South African university. These students were from disadvantaged backgrounds and were considered to be under-prepared for tertiary study. They registered for an extended BSc programme to study science at the tertiary level, and completed their degree over 4 years instead of 3. GEPS offers an adjusted curriculum that takes into account poor preparation at school, particularly in Mathematics and Science, as well as the fact that the majority of the students do not speak English as their first language. Since these students lack a solid grounding in chemistry, the underlying philosophy of instruction is to teach the content while at the same time to model thinking and reasoning processes as well as identifying evidence, argumentations etc. There are 5 contact periods per week consisting of 3 lectures and 2 small-group tutorials. The teaching strategies were consistent across the three cohorts who were taught by the same lecturer using similar course materials. Assessment comprised 4 short class tests, a mid-year examination and a final examination. Test 1 took place after about 6 weeks of instruction, the mid-year examination after 12-13 weeks and the final examination after 24-25 weeks.

Teaching approach

Submicro diagrams have been used as a teaching and learning tool in the introductory first year chemistry course since 2000, and students were given opportunities to practice drawing and interpreting them during the tutorial sessions which focused on chemical equations, stoichiometry and chemical equilibrium. For example, in one session, students were presented with samples of solutions and mixtures and asked to generate submicro diagrams of what they had observed, justifying the format of their representation with the accuracy and detail of representations being emphasised. Tasks based on submicro diagrams constituted about 25% of the problem sets for tutorials on stoichiometry and chemical equilibrium. Tutors used both submicro diagrams and symbolic representations to explore and explain the chemical reactions. Diagrams were first used in assessment in 2006, where an examination question requiring students to balance a chemical equation depicted as a submicro representation was adapted from a multiple choice format to a free response answer (Davidowitz, 2006). It was obvious from reading the students' answers that many of them could not use the information given to write the balanced equation for this reaction. The most common error was a simple tally of the icons presented instead of determining the smallest whole number ratio of reactants and products. This misconception was not listed among the distracters and would not have been revealed if the question had been used in its original format. In addressing these misconceptions, the submicro diagrams, which were already an integral part of the teaching methodology of the course, were given more emphasis, and they were subsequently used regularly as an assessment tool to determine whether they could reveal any other misconceptions held by students. The current study evaluates the impact of this approach to teaching.

Permission was sought from students to copy their answers to selected questions. This task was performed by a third party so that the responses could not be linked to a particular student. Two of the researchers constructed a coding scheme to classify the responses to the questions, arriving at the categories reported below. Where a difference arose, the category was determined by discussion and consensus. The responses to the questions were then analysed by the three researchers and comparisons made within and across cohorts allowing common misconceptions to be identified and provide evidence of the methods students used to reason and process information.

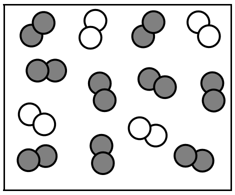
Data sources

The data consists of observations by the first author during tutorials where students engaged in tasks requiring them to interpret and generate submicro representations, and students' answers to selected questions about stoichiometry and chemical equations posed in class tests and examinations. Data were collected over three consecutive years for three different cohorts of students in GEPS. The questions were selected because they provided insight into students' understanding of chemical equations and stoichiometry. Questions 1, 2 and 3 were completed in 2007 by 111 students, questions 4a (test 1) and 4b (mid-year examination) were completed in 2008 by 164 students, and question 5 (test 1) and (mid-year examination) in 2009 by 117 students for test 1 and 120 for the mid-year examination (see Table 1).

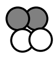
These selected questions required students to

- convert submicro drawings into chemical equations (symbolic level); Q1, Q2, Q4b, Q5
- solve stoichiometry questions presented as submicro diagrams rather than quantities of reagents; Q2, Q5

Q2



Key
Hydrogen
Nitrogen



Nitrogen, N_2, and hydrogen, H_2, react to form ammonia, NH_3.
Consider the mixture of N_2 and H_2 shown in the diagram.

a) Write a balanced equation for this reaction.
b) What is the limiting reagent in this reaction?
c) What is the maximum number of ammonia molecules that can be formed in this chemical reaction?
d) Draw a microscopic representation of the contents of the container after the reaction.

Fig. 3 Stoichiometry problem based on a submicro diagram; question 2.

Q3
The following reaction can be used to generate hydrogen gas from methane, CH_4.

$$CH_4\ (g) + H_2O\ (g) \rightarrow CO\ (g) + H_2\ (g)$$

a) Balance the equation for this reaction.
b) Which is the limiting reagent when 500 g methane reacts with 1300 g water?
c) How many grams of hydrogen can be produced in this reaction?

Fig. 4 A typical stoichiometry problem as used in question 3.

- draw the contents of the reaction vessel at the end of the reaction as a submicro diagram; Q2, Q4a, Q4b
- solve a stoichiometry problem where an algorithm would apply; Q3, Q5

A description of questions 1–5 follows. For question 1, students were asked to balance the equation represented as submicro particles shown in Fig. 2. While some of the questions in text books make use of diagrams to probe conceptual understanding, very few require students to construct diagrams as is required in question 2, shown in Fig. 3. This question was adapted from Brown *et al.* (2006, p. 111). To answer question 2 students had to interpret the diagram, which is a more challenging exercise than using algorithms, as required to answer question 3 (see Fig. 4).

Both questions 4a and 4b (see Fig. 5) were based on the same submicroscopic diagram. Question 4a appeared in the first class test, which was taken after about 6 weeks of instruction, question 4b formed part of the mid-year examination, which occurred after 12 weeks of instruction.

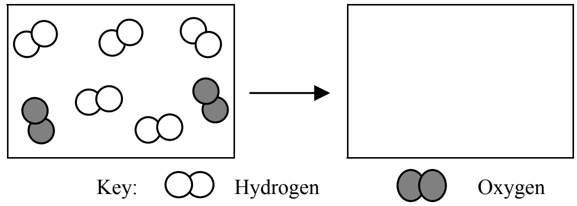
Question 5 (see Fig. 6) was given in test 1, and since overall performance was very poor, it was repeated in the mid-year examination with a view to evaluating any shifts in performance of this cohort.

Results and analysis

Observations during tutorial sessions and feedback from weekly meetings with tutors indicated that the majority of students were able to generate diagrams representing samples of solutions and mixtures that were made available to them. An analysis of the data revealed consistent improvement in 2008 and 2009 from the first assessment to the mid-year assessment. Students were better able to translate the chemical representations into chemical formulae and chemical equations and vice versa, as indicated by their responses to the questions shown below after the period of instruction. The data are used to examine five aspects of teaching and solving stoichiometry problems.

- Writing a balanced equation based on a submicro drawing, (Q1, Q5a)
- A comparison of using submicro diagrams (Q2) vs. algorithmic (Q3) approaches to solving stoichiometry problems
- Using student drawings of the submicro level as evidence of their reasoning (Q2)
- Understanding the submicro level and predicting the product of a reaction may be independent of an ability to balance chemical equations (Q2d, Q4)
- Using submicro diagrams to probe students' understanding of chemical reactions and stoichiometry (Q1, Q2, Q4, Q5)

Consider the reaction below



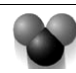
Q4a) For the reaction shown above, draw the correct number of each molecule after the reagents have been converted into a product. The balanced equation is:

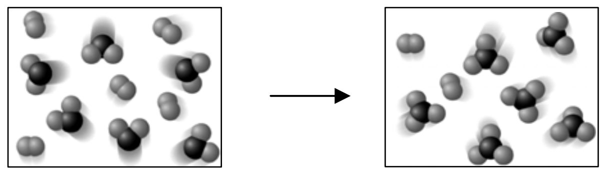
$$2\ H_2\ (g) + O_2\ (g) \rightarrow 2\ H_2O\ (g)$$

Q4b i) Write a balanced equation for the reaction shown above, which produces a gaseous product.

ii) Use the space provided above to draw the correct number of each molecule present in the reaction flask after the reagents have been converted into products.

Fig. 5 Questions 4a and 4b.

Question 5 represents a chemical reaction between AB_2  and B_2 



a) Write a balanced equation for the reaction.
b) Explain which is the limiting reactant in this reaction.
c) Calculate how many moles of product can be produced when 3 moles B_2 react with 5 moles AB_2.
d) Calculate how many moles of excess reactant remain after the reaction in part (c) above is complete.

Fig. 6 Question 5.

Table 2 Percentage of various responses by students to question 5

	Q5 (test 1) (N=117)	Q5 (mid-year exam) (N=120)
a) Balanced equation: $2AB_2 + B_2 \rightarrow 2AB_3$	**11.1**	**52.5**
Correct equation but not lowest whole numbers	4.3	3.3
$6AB_2 + 5B_2 \rightarrow 6AB_3 + 2B_2$	29.9	13.3
$2AB_2 + 2B_2 \rightarrow 2AB_3 + B_2$	7.7	6.7
Assorted incorrect responses	38.5	24.2
No answer or illegible	8.5	0
b) Limiting reactant: AB_2	**76.1**	**86.7**
Assorted incorrect responses	23.9	13.3
c) Moles of product produced: 5	**29.9**	**50.8**
Moles of product 8 i.e.5 + 3	7.7	2.5
Assorted incorrect responses	41.8	36.7
No answer or illegible	20.5	10.0
d) Moles reactant remaining: 0.5	**3.4**	**15.8**
Moles remaining 2 i.e.5 – 3	21.4	15.8
Assorted incorrect responses	53.0	57.5
No answer or illegible	22.2	10.8

Table 3 Summary of responses to questions 2 and 3, (N= 111)

	Question 2 % Correct responses	Question 3 % Correct responses
a) Balanced equation	87.5	94.6
b) Limiting reagent	60.7	98.2
c) Amount of product formed	37.5	66.7

Table 4 Analysis of the incorrect responses for question 2c (N = 111)

Max number NH_3 formed	Misconception	%
3	See products as N_2H_6 instead of $2NH_3$	21.4
2	Based on co-efficient in balanced equation	11.6
1.20×10^{24}	Convert moles product in balanced equation to number of particles – do not understand the nature of the representation	10.7
4	Based on number nitrogen molecules	9.8
Other values	1, 5 or 8 molecules of NH_3	8.9

The results for each question are presented, noting the percentage correct responses, common misconceptions and links to previous research. The common difficulties are identified from students' drawings.

Writing a balanced equation based on a submicro drawing, (Q1 and Q5a)

The 111 students of the 2007 cohort, after 12 weeks of instruction were presented with a chemical equation in the form of a submicro diagram, Q1, Fig. 2. They were asked to balance the equation shown in the figure. In order to answer this question students had to identify the product as AB and realise that a balanced equation is always written using the smallest whole numbers ratios for reactants and products. The analysis of the student responses indicate that 63% were able to write an appropriate balanced equation, 22% translated the diagram directly into a chemical equation [$6A + 3B_2 \rightarrow 6AB$] without converting to the smallest whole numbers ratios, 6% failed to identify the product of this reaction as AB and the remaining 9% made errors involving the stoichiometry of the reaction.

Question 5a, which was answered by the 2009 cohort, is more challenging than question 1, since the diagram depicting the reaction includes the reagent in excess. The analysis of the student responses to question 5a (Table 2) indicate that 11.1% were able to write an appropriate balanced equation in test 1 whereas this increased to 52.5% in the mid-year exam. Around 4% of students in both tests (4.3% in test 1 and 3.3% in mid-year test) were able to generate the correct equation, but failed to convert the coefficients to the smallest whole numbers. 29.9% translated the diagram directly into a chemical equation [$6AB_2 + 5B_2 \rightarrow 6AB_3 + 2B_2$] which includes the reagent in excess; this was reduced to 13.3% by the mid-year exam.

For similar questions Sanger (2005) reported only 15% correct, and Devetak *et al.* (2004) reported only 1.6% correct answers. The high number of correct responses to the questions in this study (63% for Q1 and 52.5% for Q5a at mid-year) could be related to the intentional use of submicro drawings in the teaching, which may be impacting on students' understanding of the submicro drawings. A fair proportion of both the 2007 and 2009 cohorts literally translated the submicro representation of the chemical reaction into an equation (22% for Q1; 29.9% and 13.3% for Q5a). These findings compare favourably with 38% of similar responses reported by Sanger (2005) revealing a common lack of appreciation of the accepted conventions in writing chemical equations.

The results for question 5 are presented in Table 2; correct answers are shown in bold type.

A comparison of student responses to stoichiometry problems: submicro diagrams (Q2) vs. algorithmic (Q3)

Table 3 presents a comparison of the correct responses for the two questions answered by the 2007 cohort, showing that the algorithmic approach produced better results. While most students could write a balanced equation for the reactions, the incorrect responses to these questions reveal misconceptions in balancing equations and stoichiometry. For example, in question 3c there was a range of incorrect strategies used to calculate the amount of product formed. These included:

- mass based on number of moles of product formed if all the water reacts (5%),
- using 1.008 g mol^{-1} as the molar mass for hydrogen (5%),
- multiplying the molar mass of hydrogen by 3, the co-efficient in the balanced equation (2%),
- a range of arithmetic errors (21.3%).

For question 2b students were not asked to explain their answer, thus there is no way of probing why a substantial number of them were not able to identify hydrogen as the limiting reagent. For question 2c, over 60% of students misinterpreted the meaning of coefficients, molecules and moles; the range of incorrect responses is shown in Table 4.

Fig. 7 Students' representations of the product of the reaction for question 2d.

An interpretation of a submicro drawing was required to answer question 2 correctly, while for question 3 students were required to perform a calculation. The results in Table 3 indicate that the students performed better on the quantitative responses.

Using student drawings of the submicro level as evidence for reasoning (Q2)

Question 2d required students to draw a submicroscopic representation of the contents of the container after the reaction. Just over a quarter of the cohort (26.8%) was able to draw a correct representation of the reaction mixture, namely ammonia and the agent in excess. Almost a fifth of students (18.8%) drew a suitable submicro representation of the product molecules, but did not include the reagent in excess. About one third of the responses contained a wide variety of incorrect submicro representations. These included 19% of students who drew diagrams containing representations consistent with the total number of particles in the product, N_2H_6. Two commonly occurring examples are shown in Fig. 7. For the students who drew N_2H_6 as their answer to question 2d, their response to question 2c was three molecules of ammonia, in all but one case showing a consistency in their misconceptions relating to the meaning of the co-efficient in a balanced equation.

The representations in Fig. 7 are similar to an example noted by Yarroch (1985) who investigated students' understanding of balancing chemical equations. His results showed that while all the students were able to balance the four chemical equations presented to them, 42% of them could not construct submicro diagrams consistent with the symbolic representation of the balanced equation. In a later study on mole ratios and limiting reagents, Wood and Breyfogle (2006) also noted that the most common error in items similar to question 2 was the choice of representations which grouped molecules together into one molecule.

An interesting feature of some of the students' responses to question 2d was the use of lines to link elements in the submicro drawing (Fig. 8). For example in Fig. 8a, by annotating the diagram, the student would have identified the reagent in excess, N_2, since it is not linked to any other entity. Approximately one third of the cohort (39 students) drew links of some type between the reagents provided in the drawing for question 2. Of these, 18 students drew the correct products even if the linkages were not accurate, for example Fig. 8b, while the rest of the students made some attempt to draw links between reactants but the diagram of the product was not correct depicting either N_2H_6 (9 students) or three NH_3 molecules instead of six (1 student). The remainder of the diagrams with links contained a wide variety of unique responses. These student-annotated drawings provide insight into the reasoning and problem-solving strategies used to answer the questions.

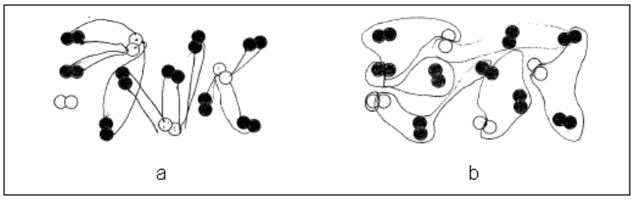


Fig. 8 Students' annotations of the submicro drawing for question 2d.

Table 5 Analysis of responses and representative submicro diagrams for question 4a

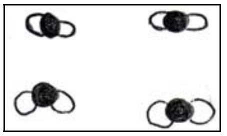
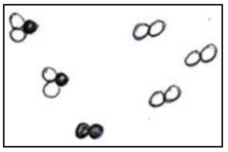
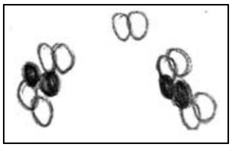
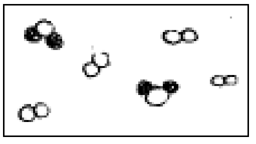
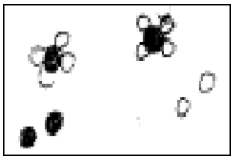
Students' responses	Submicro drawing	%
$4\ H_2O + H_2$		39.6
$4\ H_2O$ without excess H_2		6.7
$2\ H_2O$		14.6
$2\ H_2O + 3\ H_2 + O_2$		5.5
H_4O_2 aggregates 80% of drawings included H_2 in excess		12.8
HO_2		3.0
Other incorrect answers		12.1
Illegible or no answer		5.4

Table 6 Comparison of responses to questions 2 and 4

Submicro drawings of products	Q2 N =111 %	Q4a N=164 %	Q4b N=164 %
Correct drawings	46.5	46.3	67.0
N_2H_6 or H_4O_2	21.4	12.8	4.3
$2NH_3$ or $2H_2O$ (based on coefficients in balanced equations)	11.6	20.1	6.1

Table 7 Summary of the students' responses to questions 2 and 5

Section of question	Question 2 % Correct responses	Question 5 % Correct responses	
	Test 1	Test 1	Mid-year
b) Limiting reagent	60.7	76.1	86.7
c) Amount of product formed	37.5	29.9	50.8
d) Moles reactant remaining	N/A	3.4	15.8

Understanding the submicro level and predicting the product of a reaction may be independent of an ability to balance chemical equations (Q2 and Q4)

Both questions 2d and 4a required students to draw the contents of the container once the reaction has been completed. Analysis of students' drawings from their responses to question 2 shows that 26.8% of them were able to construct the correct diagram. 19.7% could draw the products of the reaction, but omitted to include the reagent in excess. A detailed analysis of students' drawings from their responses to question 4a is shown in Table 5; about 40% of students were able to construct the correct diagram. A further 6.7% could draw the products of the reaction, but omitted to include the reagent in excess. There was a variety of incorrect responses, including two which were similar to the responses for question 2. About one fifth of the students drew only the number of product molecules corresponding with the co-efficient in the balanced equation, $2H_2O$, (14.6% + 5.5%) while other diagrams contained drawings of aggregates such as H_4O_2 (12.8%).

When analysing the students' drawings of the contents of the container after the reactions depicted in questions 2 and 4, we considered them to be correct even if the students omitted to draw the reagent in excess. Questions 4a and 4b were essentially the same with respect to depicting the product of a reaction. A comparison of some of the responses to questions 2 and 4 are shown in Table 6.

The percentage of students able to construct a correct drawing of the product for question 4a (46.3%) is similar to that of the 2007 cohort who correctly answered question 2d (46.5%). Two commonly occurring misconceptions were inferred from students' drawings for both the 2007, and 2008 cohorts, namely conceptualising the products of a reaction as aggregates *e.g.* N_2H_6 or H_4O_2, as well as drawing only the number of products based on the coefficient in the balanced equation. Students conceptualising products as aggregates would arrive at the correct answer if they were solving a numerical problem such as question 3, thus student-generated diagrams allow insight into this particular misconception. It is pleasing to note that there was an improvement in students' understanding of stoichiometry as measured by their responses to question 4b where the number of correct drawings of the product of the reaction increased while the number of students holding misconceptions has decreased.

Using submicro diagrams to probe students' understanding of chemical equations and stoichiometry, Q1, Q2, Q4 and Q5

When considering students' responses to questions posed for each cohort, it is not surprising that the number of correct responses to questions requiring balancing of equations is dependent on the amount of scaffolding that is provided. For the algorithmic question 3a, which is heavily scaffolded, 94.6% of students gave the correct answer. In question 2a, with moderate scaffolding, where the students have to construct the equation given the reactants and products, there was a correct response rate of 87.5%. In question 1, little scaffolding was provided, with students interpreting the submicro diagram and converting the data into the symbolic in the form of an equation, 63.1% of students gave the correct answer. No scaffolding was provided in questions 4b and 5a where students were given only a diagram of the reacting species and were asked to generate the balanced equation. For question 4b, 67% of students could draw a correct diagram (submicro level) but only 48% could produce a correct equation. Similarly for question 5a, where the reaction was depicted as a submicro diagram, just over half the 2009 cohort was able to derive the correct balanced equation by mid-year. Submicro diagrams can also reveal student difficulties with stoichiometry which formed part of questions 2 and 5, see Table 7.

Identifying the limiting reagent was not a major stumbling block for the 2009 cohort, as shown by the high number of correct responses to question 5, namely 76.1 % in test 1 and 86.7 % in the mid-year test. The majority of students in the 2007 and 2009 cohorts were able to explain how they identified the limiting reagent, which implies that the ability to do so does not depend on being able to balance the chemical equation for the reaction. In order to answer questions 2c and 5c students have to understand the meaning of the coefficients of the balanced equation, and how these relate to the amounts of substance available for the reaction. About one third of the cohort was successful in answering this question in test 1 of 2007 and 2009 respectively. By the time the students wrote the mid-year examination in 2009 there was an improvement in performance with half of students able to determine the amount of product formed in the reaction. One of the misconceptions noted for question 5c was simply to add the number of moles of reactants (7.7% for test 1 and 2.5% for mid-year test).

Table 8 A summary of responses to questions 1–5

N	Cohort	Q	Submicro drawing provided	% correct drawings	Symbolic	% correct balanced equations
111	2007 Test 1	2	Representation of reactants only	46.5	Students generate balanced equation given formulae of reactants and products	87.5
111	2007 Mid-year exam	3	N/A	N/A	Students generate balanced equation given formulae of reactants and products	94.6
111	2007 Mid-year exam	1	Representation of reactants and products	N/A	Students generate balanced equation given formulae of reactants and products	63.1
164	2008 Test 1	4a	Representation of reactants only	46.3	Balanced equation given	N/A
164	2008 Mid-year exam	4b	Representation of reactants only	67.0	No formulae of reactants or products given	48.1
117	2009 Test 1	5	Representation of reactants and products	N/A	Students generate balanced equation given formulae of reactants and products	11.1
120	2009 Mid-year exam	5	Representation of reactants and products	N/A	Students generate balanced equation given formulae of reactants and products	52.5

Notes
Q1 Submicro diagram of reagents and products, no reagent in excess, amounts of reactants in same ratio as balanced equation.
Q2 + 4 Submicro diagram of reactants only and one of the reagents is in excess
Q5 Submicro diagrams of reactants and products, one reagent in excess..

Students' ability to determine the amount of reagent in excess (Q5d) is very poor. A significant percentage resorted simply to subtracting the number of moles of reactants (21.4% for test 1 and 15.8% for mid-year test). For both questions 5c and 5d students appeared to believe that for a chemical reaction to occur, the reactants must be present in the ratios represented by the balanced chemical equation. The same cohort of students achieved an average mark of 83% for a stoichiometry question in the final examination at the end of the course, which required them to perform calculations similar to questions 5c and 5d. This confirms previous findings in the literature that students are able to solve problems using algorithms without the reasoning and processing skills that demonstrate a concomitant conceptual understanding (Nakhleh *et al*, 1996; Papaphotis and Tsaparlis, 2008).

From these results we can draw some conclusions:

- Students' ability to complete the questions on chemical equations is dependent on the degree of scaffolding provided.
- Students' abilities to interpret and construct diagrams of the submicro level are, in some cases, independent of their ability to balance chemical equations.
- Being able to predict the correct product of a reaction may be independent of the ability to balance the equation for that reaction.

While scaffolding can take various forms, having students construct diagrams of the submicro level can be a significant tool for learning basic concepts. For these cohorts, of whom many do not have English as their first language, the diagrams may be especially helpful.

Discussion

Students' responses to the five questions allow us to probe their understanding of chemical equations and stoichiometry. The main findings for the five questions showing comparisons where relevant are summarised in Table 8.

The findings from this study show that most students were proficient at balancing simple equations when presented with the reacting species and products as required to answer questions 2a (where the product was named) and 3a. The formation of ammonia from hydrogen and nitrogen is part of the secondary school chemistry curriculum, thus familiarity may account for the high percentage of balanced equations for question 2a. Students were also able to interpret submicro diagrams to construct the balanced equation required for answering question 1. Interpretation of question 1 is not as conceptually demanding as questions 2, 4 and 5, as all the reagents are converted into products. These results suggest that allowing students to engage with the material using multiple representations, as recommended by Johnstone (1993) and Devetak *et al.* (2004), has been instrumental in the improved performance of students relative to the studies reported by other researchers (Mullford and Robinson, 2002; Sanger, 2005; Wood and Breyfogle, 2006). These researchers used submicro diagrams in a multiple choice format to probe understanding of aspects of balancing equations and stoichiometry where the answer choices provided could have acted as prompts for students. Without the prompts provided in multiple choice format students are reliant on their own understanding to formulate a response (Davidowitz, 2006). Having students generate their own diagrams of the products of a chemical reaction provides insights into their understanding of chemical reactions and stoichiometry. Less than half the 2008 cohort was able to write a balanced equation for question 4b, the formation of water. It would appear that it is more difficult for students to construct the balanced equation for a reaction when presented only with a submicro diagram depicting the reactants and no prompting about the products formed as given for the formation of ammonia in question 2a in 2007.

A comparison of the responses to questions 2, 3 and 5 shows that students can solve problems according to algorithms (Q3 b and c), but interpreting diagrams poses a much greater conceptual challenge (Q2 b and c, Q5b-d). The ability to use algorithms successfully without necessarily understanding the concepts that underpin them has been observed by other researchers (Niaz and Robinson, 1992;

BouJaoude and Barakat, 2000; Sanger, 2005; Papaphotis and Tsaparlis, 2008). Student-generated diagrams allow teachers an understanding of the ideas that students hold around equations and stoichiometry; these would not be evident by asking them to solve numerical problems where they can simply apply an algorithm. The submicro diagrams provide a mechanism for answering the second research question namely to identify specific misconceptions that students hold around the topic of stoichiometry. The two occurring most commonly in both cohorts relate to the balanced equation, which is the key to solving all problems in stoichiometry. Students conceptualise the products as aggregates of atoms; this misconception allows them to arrive at the correct answer to problems they can solve using an algorithmic approach. The second misconception noted is the confusion between the coefficients of the balanced equation and the amount of product which could be formed in a given reaction, questions 2 and 4. Students were asked to draw correct number of each molecule present once all the reagents have been converted to products. After about 6 weeks of instruction, a significant number of students in each cohort (11.6% in 2007, and 21.1% in 2008) simply drew the number of molecules corresponding to the co-efficient in the relevant balanced equation for questions 2 and 4a respectively.

The data suggest that students need time to appropriate submicro diagrams as shown by the improvement in performance in questions involving submicro diagrams during 2008. For question 4a, 46.3% of students were able to draw the correct products of the reaction, while for question 4b, the percentage of correct answers increased to 67% despite the fact that students were also asked to write a balanced equation for the reaction. The responses to question 4b, see Table 6, show a decrease in the frequency of misconceptions around the products of the reaction. For this particular cohort the only intervention that could have led to an improvement in performance was extensive feedback after the first class test (Q4a) and more exposure to submicroscopic diagrams in teaching and assessment. It is a matter of concern that by mid-year 22.6% of students were still not able to construct a simple chemical equation, nor could they draw the products of a reaction. It takes time to assimilate concepts, thus teachers should be cautious of having unrealistic expectation of students. They would do well to heed the words of Laugier and Dumon (2004):

> *"The chemical equation enables them (pupils) to relate what is happening in the bulk situation with the underlying atomic and molecular changes. To do this requires a large measure of abstraction. We would be deceiving ourselves if we believed that pupils would be able to accomplish, without difficulty, an intellectual process, which took centuries for scientists to construct."* (p. 327)

Analysis of the submicro diagrams reveal examples where students have drawn lines indicating how the reagents combine to yield new products, see Figure 8. While these did not always provide the correct answer, they do show how students are attempting to process the information presented to them, and might be a worthwhile strategy for a teacher to implement.

Conclusions and implications for teaching

The findings from this study show that submicro diagrams are a valuable teaching tool for introductory topics in first year chemistry, since the summary of findings in Table 8 show that students performed much better than in studies using similar questions reported in the literature (Mullford and Robinson, 2002; Sanger, 2005; Wood and Breyfogle, 2006). To some degree the results reinforce previous research (Niaz and Robinson, 1992; BouJaoude and Barakat, 2000; Sanger, 2005; Papaphotis and Tsaparlis, 2008), which showed that students cope more easily if they are able to use an algorithm to solve problems (such as question 3) rather than having to construct their own interpretation of chemical reactions and stoichiometry required to answer questions 2, 4 and 5. The student-generated drawings of the submicro level also demonstrate that some students find it difficult to make the link the submicro and symbolic levels of representation.

Implications for teaching

While students commonly encounter submicroscopic representations in texts, animations and in teaching, their understanding of the submicroscopic representations (Kelly and Jones, 2008) and the ability to draw accurate representations to explain or respond to questions has been shown to be less than satisfactory for many students in this study. Problems that require students to construct diagrams of the submicro level require a higher order of thinking than using algorithms, which can be achieved through a recipe driven approach. Students should be exposed to multiple representations including submicro diagrams, as suggested by Chandrasegaran *et al*. (2009), as well as physical models, since these may enable students to make links between the submicro and symbolic levels allowing them to fully interpret the information implied in a chemical equation. Structural formulae, *e.g*. Lewis structures, are very common in first year chemistry. In addition, in organic chemistry students are expected to be able to convert from molecular to structural formulae; as well as being able to switch between line drawings, extended structures and diagrams showing the tetrahedral nature of compounds containing carbon atoms. It is therefore surprising that student-generated drawings of the submicro level are not used routinely as a teaching tool rather than simply as illustrations in text books and questions at the end of chapters.

The pedagogical significance of students generating their own drawings, and using them to facilitate a negotiated meaning is consistent with a student-centred approach to learning (Kozma, 2003). Many examples of the use of submicro diagrams are centred on interpretation rather than having students construct their own diagrams. While this study has focussed on students' understanding of chemical equations and stoichiometry, the use of submicro diagrams as a teaching tool has a wider application for other topics such as gas laws, chemical equilibrium, acids and bases, as submicro diagrams depicting these topics are appearing more frequently in first year text books. In addition, it has allowed the researchers to probe students' understanding of chemical equations and stoichiometry and exposed alternative conceptions which will inform future teaching of the topics. Students can annotate their own drawings to determine how the reactant particles re-arrange to form new products. This approach highlights the similarities and differences between the characteristics of submicro drawings and chemical equations, and makes the information implicit in a balanced chemical equation more explicit for novices. The submicro diagrams may also serve as a tool to facilitate students' ability to acquire the attribute of discursive fluency which Airey and Linder (2009) believe is *"necessary for achieving fluency in the various modes of disciplinary discourse"* (p. 27).

Acknowledgement

The authors appreciate the valuable feedback received from the reviewers

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